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HARD FLUSH AIRCRAFT SHELTER (TEST MODEL DESIGN AND PROTOTYPE CONCEPTUAL STUDY)

The Boeing Company
Seattle, Washington 98124

January 1977

Final Report

Distribution limited to US Government agencies because of test and evaluation (Jan 77). Other requests for this document must be referred to AFWL (DEO), Kirtland Air Force Base, NM 87117.

This research was sponsored by the Defense Nuclear Agency under Subtask SC301, Work Unit 01, "Flush Aircraft Shelter."

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Director
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Washington, DC 20305

AIR FORCE WEAPONS LABORATORY
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This technical report has been reviewed and is approved for publication.

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20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

This report documents results of a design study for the Boeing Hard Flush Aircraft Shelter (HFAS). The basic HFAS concept was formulated by the Boeing Aerospace Company as a protective shelter for the F-111. The present study addressed reconfiguration of the shelter interior so as to accommodate a variety of USAF tactical aircraft, while also providing an overall increase in shelter blast resistance. Design concepts for the full-scale prototype are presented, together with analyses design details, next page

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20. ABSTRACT

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and pretest predictions for a one-third scale test model for the DICE THROW high explosive airblast environment. Conceptual prototype and detailed test model design drawings are provided as an Appendix.

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CONTENTS

ILLUSTRATIONS

ILLUSTRATIONS (Cont.)

TABLES

SECTION I

INTRODUCTION

In this design study, the Boeing hard flush aircraft shelter design is altered to meet a higher threat level and to accommodate a variety of tactical aircraft. The shelter was designed to accommodate the following aircraft: A-7, A-10, F-4, F-15, F-16, F-100, F101, and F-111 (fully extended wings).

The resultant prototype preliminary design is described by drawings, sketches and a narrative. The narrative includes the results of studies on roof actuation systems, protection from nuclear weapons effects, starting aircraft engines within the shelter, and adapting the shelter to house two aircraft.

Detailed drawings are provided for a 1/3 scale model to be tested in the Dice Throw High Explosive Test to be held at White Sands Proving Ground in late 1976. The scaling relationship is discussed for the purpose of relating structural response to the prototype structure from model measured response.

A test plan is provided for testing the shelter in the Dice Throw Test. The plan includes the test objectives, the required measurements to meet those objectives, and measurement predictions. The prediction analysis approach is also described including input data, assumptions and idealizations.

SECTION II

BACKGROUND

Unprotected aircraft on the ground are quite vulnerable to enemy attack. Historically, large numbers of aircraft have been destroyed on the ground in various engagements since World War I. Consequently, a variety of revetments and shelters have often been deployed to help reduce aircraft losses on the ground.

There is a distinct possibility that aircraft and airfields might, in the future, be targeted by nuclear weapons. The airblast from a nuclear weapon (P_{so} = 0.3 bar (4 psi) is quite enough) is very effective toward destruction of unprotected aircraft within a fairly large area. The present generation of tactical aircraft shelters has been primarily designed to meet a conventional weapons threat. This design is basically an above ground arch. The design has some inherent hardness for nuclear weapons, and limited upgrade is possible. However, for an overpressure in excess of 7 to 14 bars (100 to 200 psi), the loads on any projection above ground level are prohibitively high. Therefore, the ideal concept may be a shelter flush with the ground, thus avoiding reflected overpressures and drag pressures.

The dimensions of the aircraft being sheltered require interior shelter size of approximately 24 m X 24 m X 7 m (80 ft X 80 ft X 2[illegible] ft) to house them. A structure with a 24 m (80 ft) span normally would have to be an arch or similar shell structure to survive overpressures of 14 bars (200 psi). The radius of an arch design would have to be 10 to 12 m (33 ft to 40 ft). This plus an adequate soil cover requires the floor to be 13 to 15 m (45 ft to 50 ft) below ground level for a flush shelter. This depth requirement creates a problem for aircraft access. A compromise is a partially buried structure. Still most arch concepts will have a wall or door exposed to drag pressures and reflected overpressures.

A shelter with a conventional flat plate roof design would require a lower depth below ground level since aircraft height determines the vertical dimension. The structure requires that the 24 m (80 ft) span be broken up into smaller spans to achieve an adequate design.

The Boeing hard flush aircraft shelter is a compact building design which solves the problem of aircraft access. This is achieved by a roof elevation system and an aircraft elevation system which allows vertical access for the aircraft. The vertical access permits fixed columns to be sited such that the 24 m (80 ft) span is broken up into three 8 m (26 ft) spans. Consequently, a flat plate roof design is possible. The detailed description and sketch are given in Section IV.

SECTION III

OBJECTIVES

The objectives of the contract effort reported in this document are as follows:

(a) To modify the prototype design to accommodate the A-7, A-10, F-4, F-15, F-16, F-101, and F-111 (fully extended wings). The design hardness should meet the specified higher threat.

(b) To design a 1/3 scale model to be a structural replica of the prototype design.

(c) To write a test plan for the model to be tested in the Dice Throw Test. The test plan includes the measurement requirements.

(d) To make pre-test predictions of the structural response of the test model at each measurement location.

SECTION IV

PROTOTYPE SHELTER

This section describes the Boeing prototype shelter. Protection requirements and operational constraints which led to the particular design are discussed and the considerations leading to the moveable ceiling and floor systems are outlined. Personnel and equipment layouts are discussed and cost critical items to be emphasized during any final engineering design activity are listed. Adaptability of the concept to multiple aircraft parking and inside engine start completes the prototype discussion.

1. PROTECTION REQUIREMENTS (HARDNESS CRITICAL AREAS)

Table 1 lists the areas which limit the hardness of the shelter.

TABLE 1

HARDNESS CRITICAL ITEMS

	Item	Comments
1.	Moveable roof	The roof provides overpressure, radiation and penetration protection. Critical areas are above the columns and interior bearing walls where high shear stresses occur.
2.	Roof actuators and adjacent walls	Severe distortion of the walls resulting in distortion of the rod/cylinder combination could prevent the roof from opening.
3.	Roof seals and latch system	The seals prevent the overpressure from leaking into the shelter and causing aircraft damage. The critical time is when the roof rebounds and tends to open the seals. Rebound is resisted by the latch system.
4.	Aft wall area	This is the most flexible area of the shelter. Extreme distortions of the wall due to air induced soil pressure will tend to bind the moveable roof.

TABLE 1 (Continued)

Item	Comments
5. Elevator floor guides	Binding between the walls and guides could prevent the elevator floor from moving upward.
6. Column and interior bearing walls	These highly stressed areas are essential for adequate structural performance of the fixed and moveable roofs.

Table 1 lists items which are primarily susceptible to overpressure loading. Some of these items will be tested and demonstrated in the Dice Throw Test. Weapons effects other than overpressure also have an impact on the shelter design. These are groundshock, radiation, EMP and penetration.

Most groundshock susceptible items may be shock isolated. The Dice Throw Test results will provide some insight into the environment at various locations in the facility. Shock isolation is the solution for any item not inherently resistant to the shock levels. The elevator floor could be shock isolated if the landing gear on any of the aircraft is not adequate for groundshock. The aircraft landing gear are probably adequate for vertical ground motion (based on drop test results). However, lateral motions may overstress the landing gear. More work needs to be done in this area.

The expected radiation levels within the building are given in Table 2. The first level floor is below the fixed roof, and the aircraft elevator is below the moveable roof.

TABLE 2

RADIATION LEVELS

Location	Level: gammas	Level: neutrons
First level floor	9.0 REMS	2.1 (10^7) n/cm^2
Aircraft elevator	165 REMS	7.6 (10^9) n/cm^2

Radiation in the aircraft elevator area due to fallout will be approximately 0.5 REM/HR. Radiation levels in the personnel room at the first level will be well below any level causing radiation sickness. Additional radiation shielding for neutrons may be achieved with borated concrete if necessary.

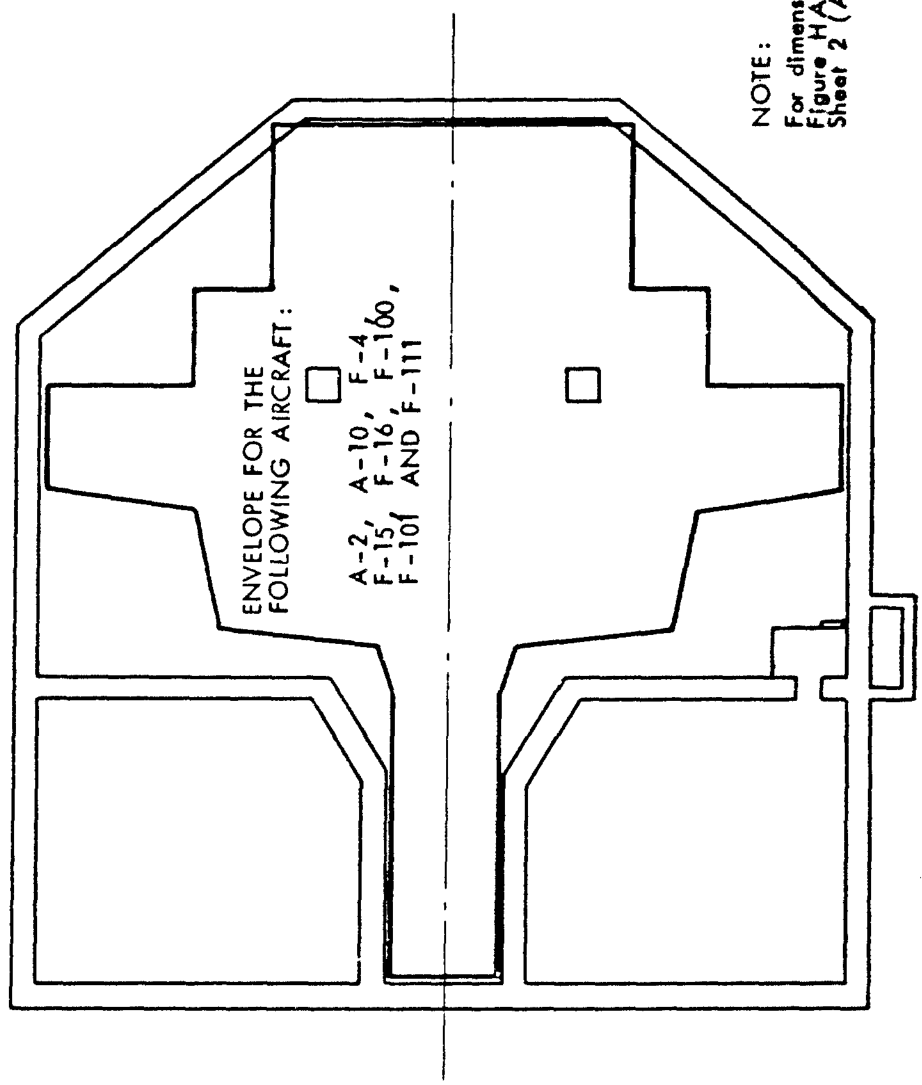
The debris (ejecta) has its greatest effect on the design of the roof actuators. The prototype design study was based on 0.2 m (0.7 ft) average debris depth (peak depth = 1 m (3.3 ft)).

EMP protection was considered in the concept; however, no detailed design was performed in areas such as electrical shielding or isolation. Grounding details and other necessary details for EMP protection have not been precluded from the design. For final design, the EMP shielding inherent in the structure should be evaluated before providing final shielding details.

2. OPERATIONAL CONSTRAINTS

a. Aircraft Envelope

Figure 1 shows the aircraft envelope provided by AFWL. This envelope includes a clear space of 1 m (3.28 ft) around the aircraft. Figure 2 shows the actual outlines of the aircraft within the shelter. The aircraft are located so that the fixed columns could be sited without interference between the columns and the aircraft. Figures 3 through 8 show envelopes of individual aircraft which had some effect on the structure layout.



NOTE:
For dimensions see Figure HAS-P-001 Sheet 2 (Appendix "A")

Figure 1 ASD/DES Aircraft Envelope

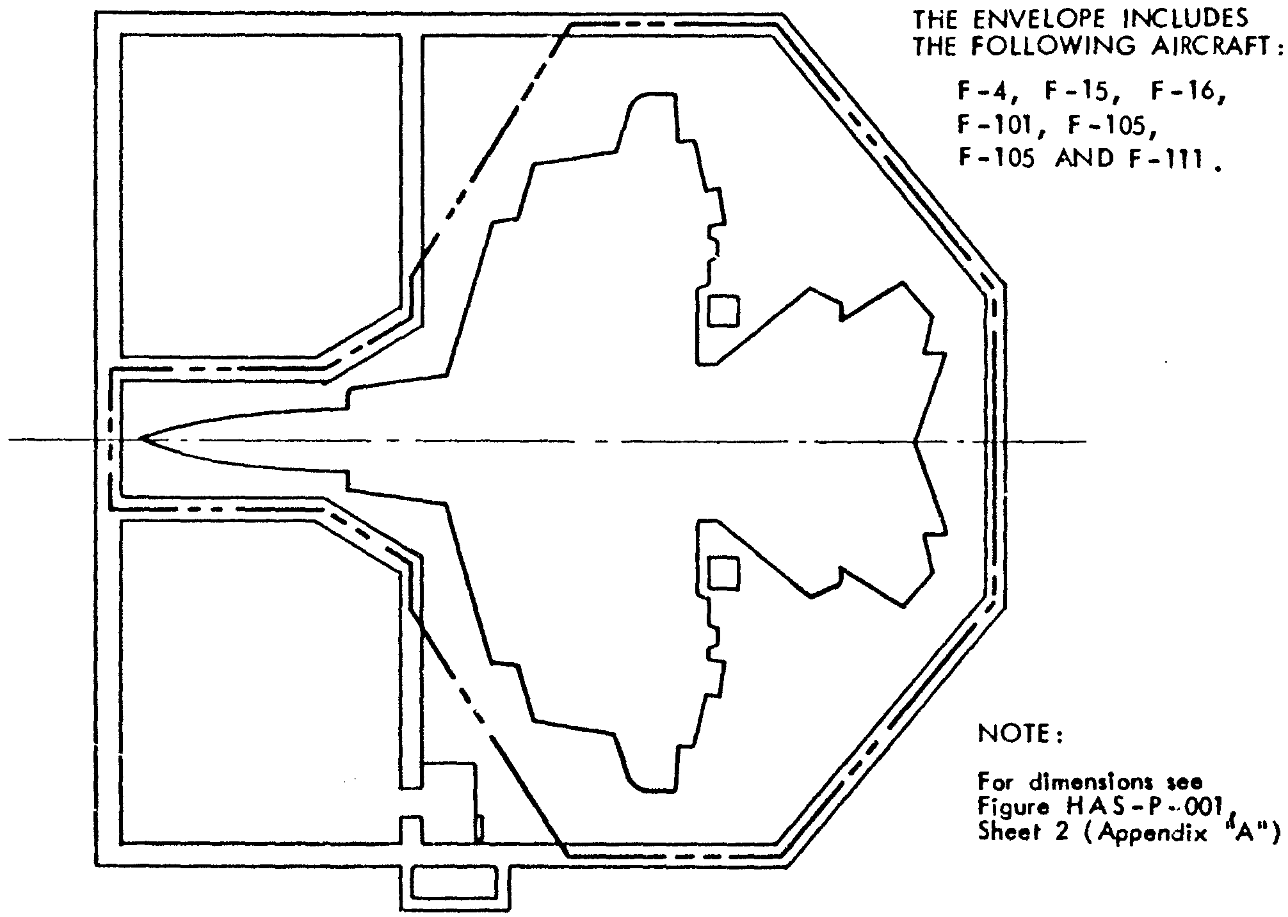


Figure 2 Composite Aircraft Envelope

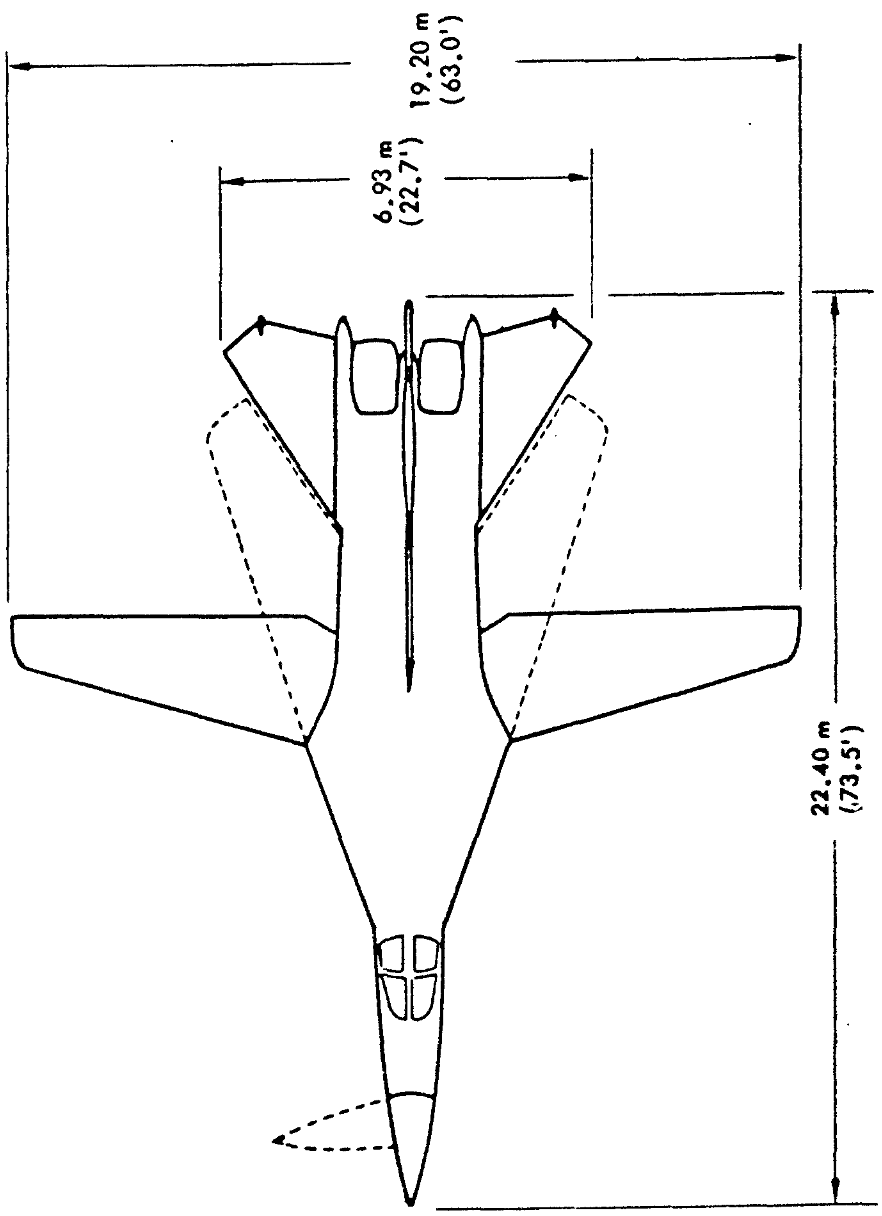


Figure 3 F-111 Envelope

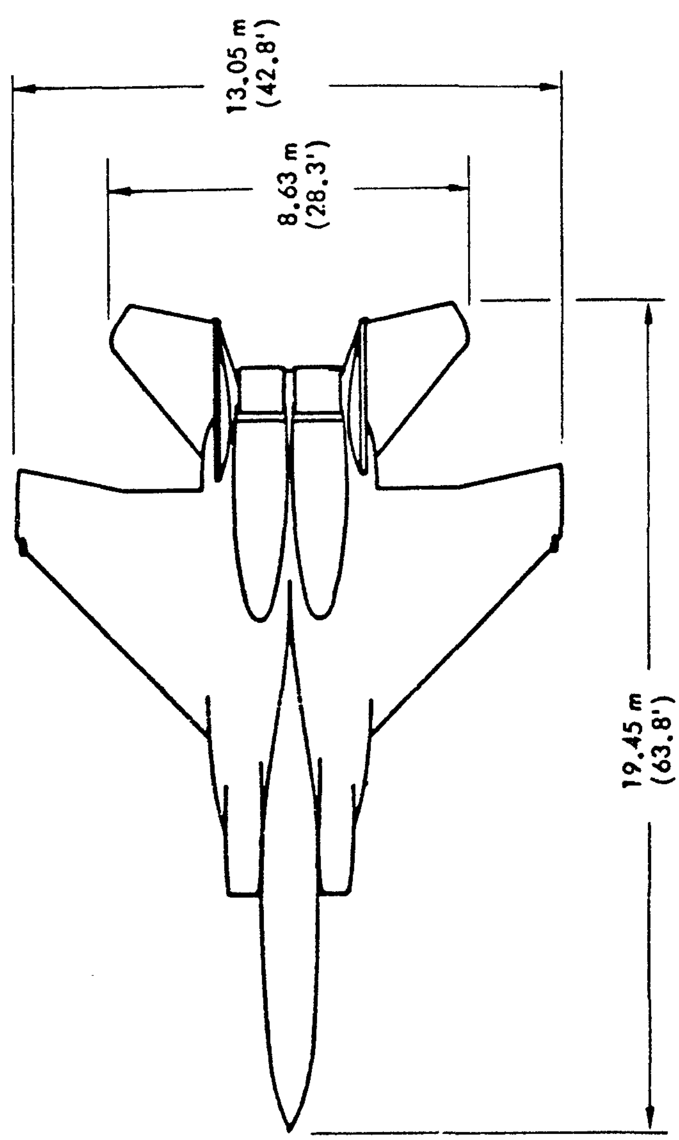


Figure 4 F-15 Envelope

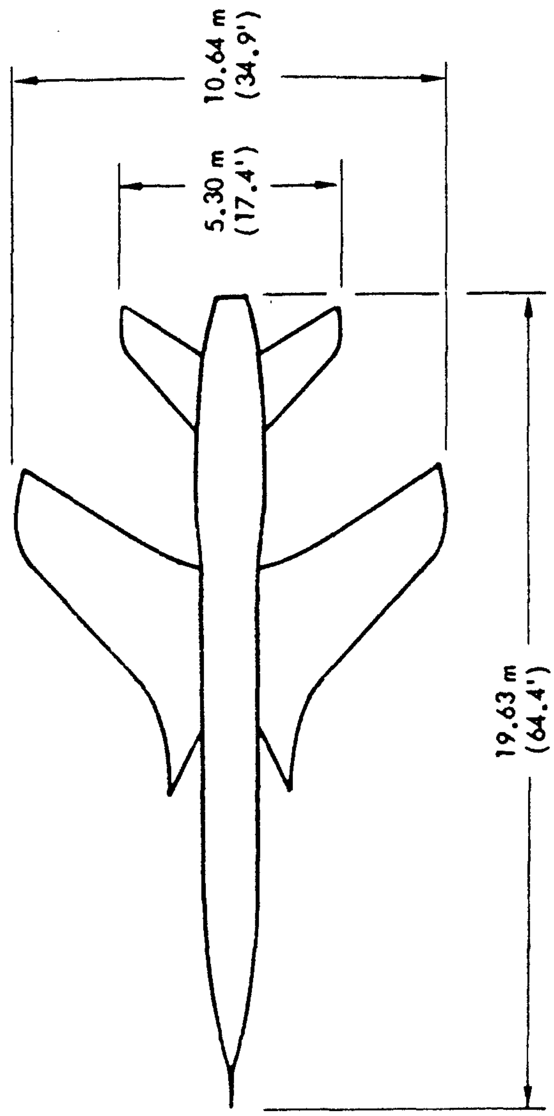


Figure 5 F-105 Envelope

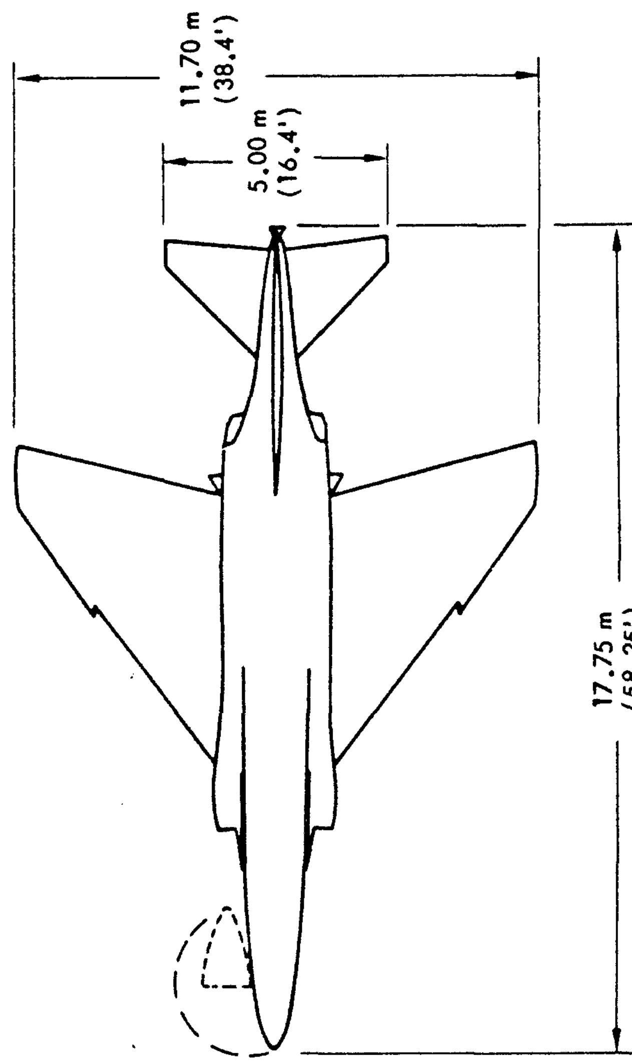


Figure 6 F-4 Envelope

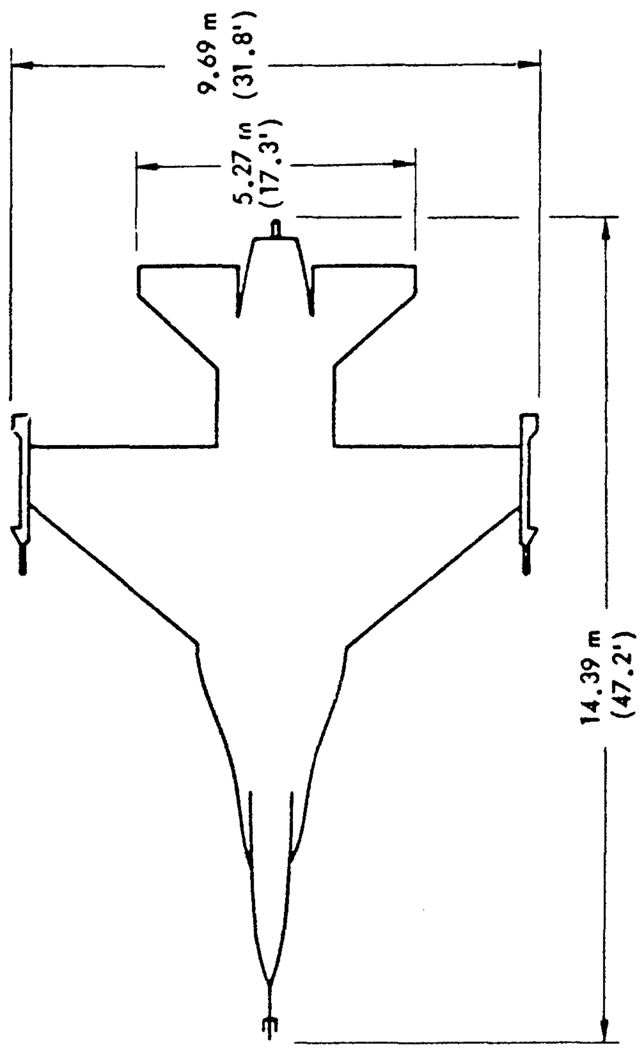


Figure 7 F-16 Envelope

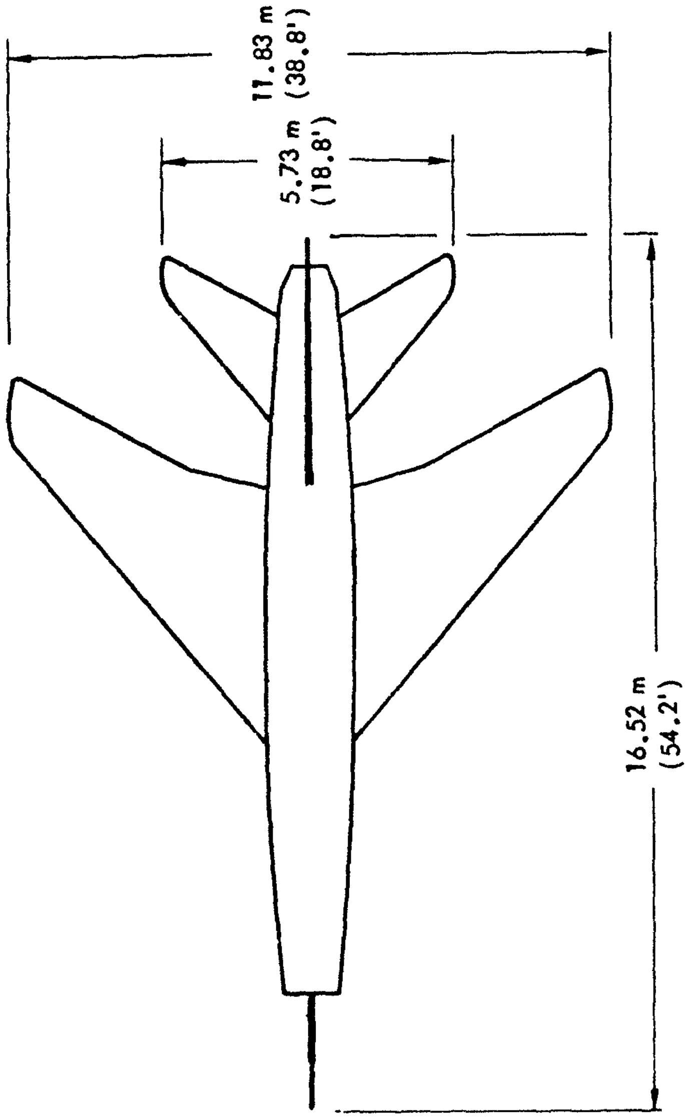


Figure 8 F-101 Envelope

The F-111 overall dimensions established the length and width of the shelter. The F-111 gross weight was critical for the design of the elevator system. The overall height of the F-105 (6 m, 19.7 ft) determined the inside height of the shelter; the distance between the landing gear of the F-4J (5.5 m, 17.9 ft) determined the width of the airplane elevator structure. The location of the columns was set largely to avoid interference with the wing and tail of the F-15. The nose of the fuselage of several aircraft is hinged or removable. This operation may require some rearrangement of the bearing walls in the forward part of the shelter. Armament on the aircraft have some effect on the aircraft envelope. Future information or development of new armament systems can also affect the required envelope.

Steel columns were selected over concrete columns because of the ease of changing the location of the columns. The present arrangement of the walls and columns is quite close to the optimum structural arrangement. Some future aircraft may require moving the columns to avoid interference between the columns and the aircraft. A different column location would affect the shelter hardness to some degree. Moving a column permanently involves:

(1) removing the existing anchorage and concrete pad;

(2) installing anchorage at the new location;

(3) relocating the existing column;

(4) cutting and patching the top plate of the elevator floor to accommodate the new column location.

An aircraft shelter designed for one specific aircraft would be quite different than the present design since most aircraft are smaller than the F-111.

b. Opening/Closing Times

The criteria for opening or closing the shelter was considered to be nominally 3 minutes. This time is exclusive of startup time for the power system selected for the ceiling and elevator systems.

c. Personnel and Equipment Space

Layout of the prototype design for personnel and equipment was based on sound engineering practice, as no specifications were available for this type of structure. Noise levels were a major consideration in separating the hangar area from the personnel and equipment areas. Provisions were made for a fire extinguishing system, a power source for actuation of the ceiling and elevator, heating and ventilating equipment and aircraft support systems. Operations and communications space had to be allocated as did sleeping accommodation space.

3. MOVEABLE CEILING

In the selection of a moveable ceiling system, consideration was given to either a vertically lifting ceiling or a sliding type cover. The elevator system was considered separately from the ceiling actuation system but the 3 minutes open/close time was a requirement for both. Both vertical lift and sliding systems are discussed below.

a. Vertical Lift System

(1) Ball Screw System

Large ball screw actuators are an alternate state-of-the-art method to provide the load and stroke capability for the ceiling lifting function. The ability to fabricate ball screws large enough to lift the ceiling directly in a manner similar to the hydraulic cylinders is not known to exist; however, if structural stability is achieved by a secondary structure, the basic load capacity is available. Ball screws have an advantage in synchronizing the motion of four actuators and in holding the load under failure conditions.

A possible approach to using ball screws was developed during this contract, but after the prototype evaluation. The concept is shown in Figure 9. It was not developed further due to the apparent lack of readily available components as compared to the hydraulic lift system. The concept was not compared cost-wise to the hydraulic actuation concept; however, it should be comparable in cost.

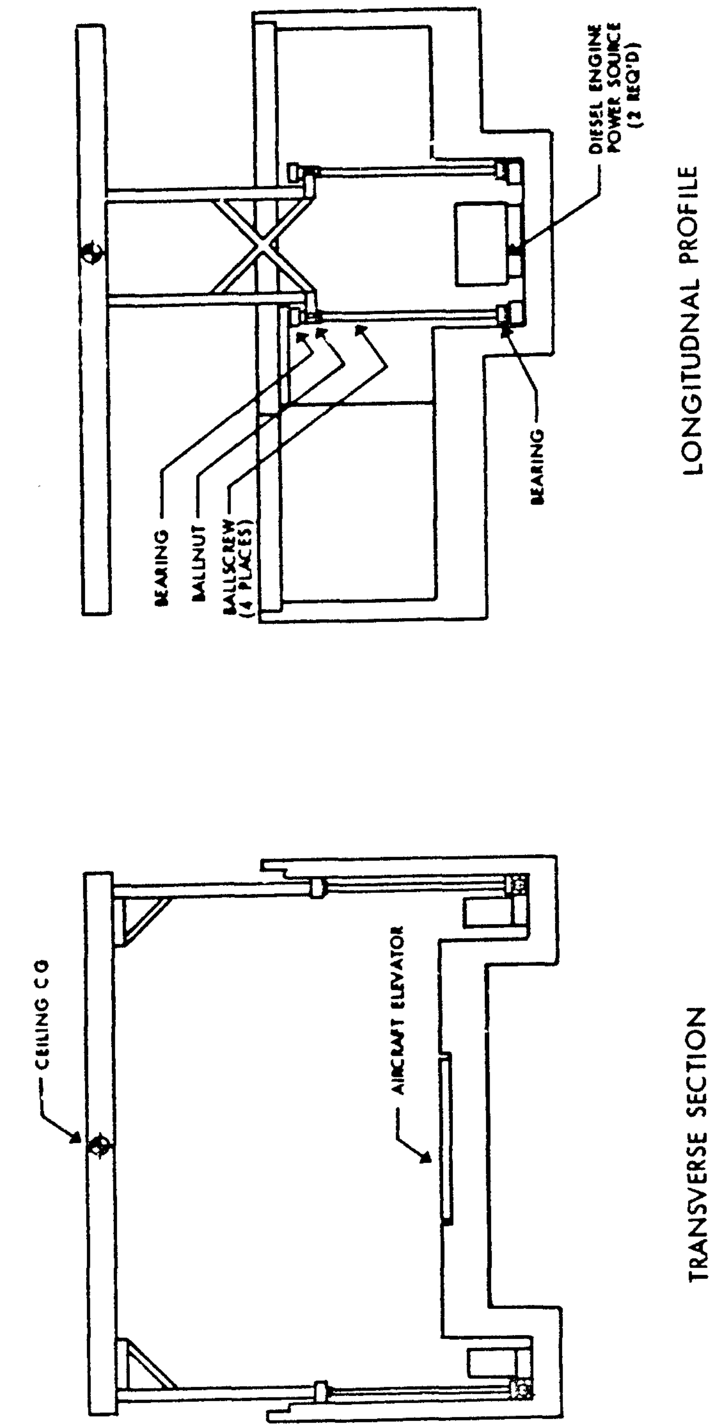


Figure 9 HFAS Ball Screw Ceiling Actuation Concept

(2) Hydraulic Cylinder System

Hydraulic cylinder systems were examined in detail and offer the following advantages:

(a) Direct simple actuation concept with a minimum number of major components taking the least space with probably the least cost.

(b) State-of-the-art fabrication. All elements of the system can be designed and procured from known sources. All major components except the actuators are in production, and these may be custom fabricated in existing facilities. A prototype system could be delivered within one year.

(c) Positive results for the control of the motion of each actuator in both directions, minimizing the effects of friction, leakage, C.G. offset, and blast damage, with allowance for operation with one actuator disabled.

b. Sliding Ceiling System

The use of a sliding cover as an alternate to the vertical lift cover has been evaluated on a preliminary basis. This concept would also be used for the Multiple Aircraft Shelter. The concept is shown on Figure 10.

The main features of the concept shown are the sliding cover, a guide rail system, a debris pit, and the engine driven cable actuation system. The cover would be on rollers during actuation to minimize power requirements. The roll system would be arranged to unload the rollers in the closed position, and a pneumatic seal would be utilized to minimize breakout friction.

The cable system shown uses four actuating cables: two for opening and two for closing. A single sheave arrangement is used to reduce the maximum loads and allow smaller mechanical drive components. For normal operation, a cable tension of approximately 110,000 N (25,000 pounds) in each of two systems would be sufficient to open the cover.

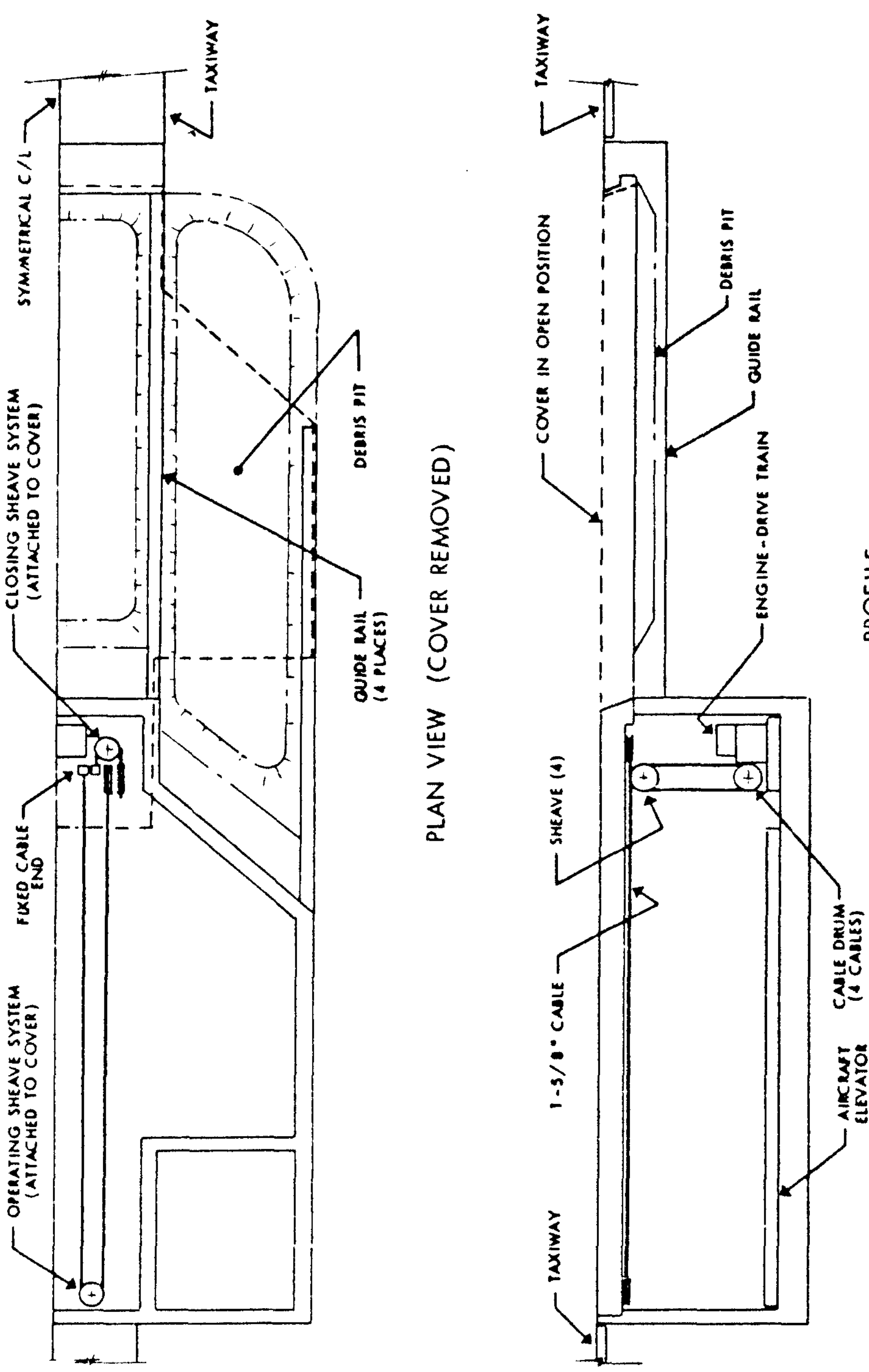


Figure 10 HFAS Sliding Cover Concept

Four cable drums would be required, each having a capacity for 61 m (200 feet) of cable. The power source could be electric, hydraulic, or direct engine drive. The direct engine driven cable drum system shown would require approximately 131 KW (175 HP) to provide a force margin of 2.0 on the normal opening loads to overcome debris resistance. A debris pit is provided to minimize debris loads. The principal advantages of a sliding cover concept is a decreased cover opening power requirement. The principal disadvantage is an increased vulnerability to damage from conventional weapons due to increased target area of rail and roof system combination.

The configuration shown is a preliminary concept to illustrate the general requirements for this type of system. The cover could be arranged to slide off on the orthogonal axis, and the actuation machinery could be arranged differently, depending on other system requirements. Alternate actuation methods, such as ball screw or hydraulic actuators, would be investigated if further work is undertaken.

c. Concept Selected

The HFAS basic concept and the state-of-the-art in generating large actuation systems has resulted in the hydraulic vertical lift system being defined as the most feasible actuators.

The prototype ceiling lift system will have major elements as follows:

Actuators:	4 each single stage double acting hydraulic cylinders equipped with locking device at maximum stroke
Bore:	0.508 m (20 in) diameter (working diameter), 0.584 m (23 in) O.D.
Rod:	0.457 m (18 in) O.D., 0.356 m (14 in) I.D.
Working Stroke:	7.36 m (24 ft)
Overall Length:	8.8 m (29 ft)
Material:	ASTM A-27 cast steel
Maximum Load Capacity:	4.45 (10^6) N @ 2210 N/cm^2 (10^6 lb @ 3200 psi)

Working Load Capacity:	2.2 (10^6) N @ 1100 N/cm^2 (0.5 X 10^6 lb @ 1600 psi)
Pumps:	4 each Variable delivery two way hydraulic pump with electro-hydraulic servo control. Capacity 580 liter/minute (153 gal/min) @ 1000 RPM pressure 2070 N/cm^2 (3000 psi) rating - 2410 N/cm^2 (3500 psi) peak (Oilgear Company Unit 23030).
Power Source:	Diesel engines driving through custom gear boxes.
Engines:	2

Detroit Diesel Model 12V-71T

Two Cycle-turbocharged

Rated Horsepower: 429 KW (575 HP) @ 1800 RPM

Estimated Net Total Horsepower Requirement: 298 KW (400 HP)

Gearboxes:	2
Input:	298 KW (400 HP) @ approximately 1800 RPM
Output:	2 shafts - 119 KW (160 HP) @ 1000 RPM 1 shaft - 60 KW (80 HP) @ 1800 RPM

As shown on Figure 11, each gearbox would drive two ceiling system pumping units and have one auxiliary output shaft which would drive the elevator pumping unit and as an option an emergency generating system for the shelter.

With hydraulic cylinders defined as actuators, the power source and control methods were considered.

To supply a large quantity of high pressure oil to the actuators, two basic methods can be defined:

1) Direct pumping at the required pressure and flow

2) Stored energy using gas to pressurize hydraulic accumulators.

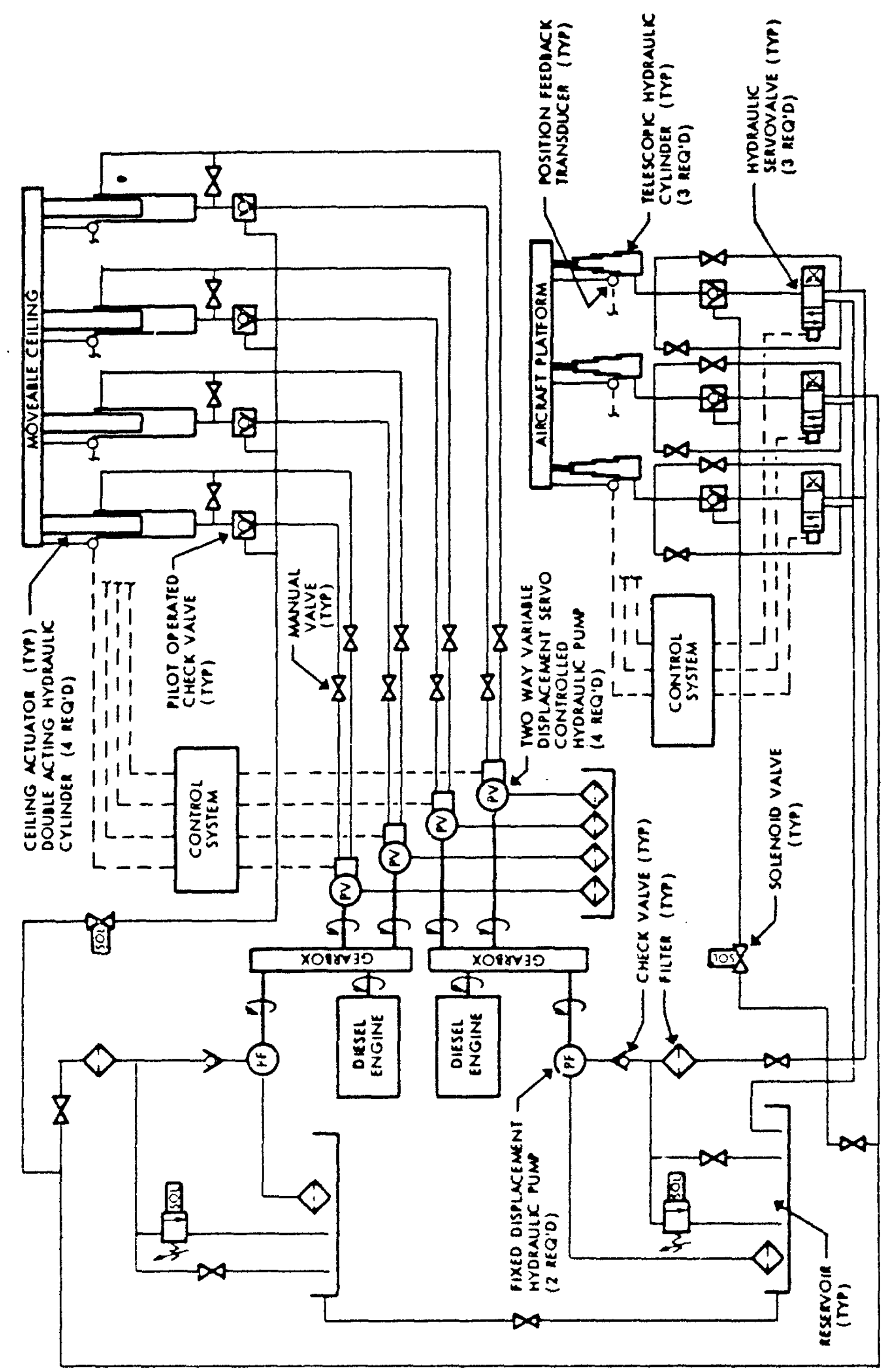


Figure 11   HFAS Prototype Actuation Systems Schematic Diagram

Hydraulic accumulators require a source of gas pressurization which can be by gas pumping, hydraulic pumping, or by a gas generator. All three methods were investigated on a preliminary basis.

The major advantages of an accumulator system are:

1) Stored energy reduces the size of the prime power source as a smaller pump may be used.

2) The ceiling actuation time can be reduced.

The major disadvantages are:

1) Total energy requirements are greater since energy must be stored at a high pressure and throttled into the load.

2) Equipment space and weight are increased because of the gas storage requirement.

3) The system cost is greater because additional high pressure components are required.

The possible exception is the gas generator powered accumulator where the costs and volume may be comparable to a direct pumping system.

Control of the motion of the ceiling slab is critical to the success of the concept when multiple hydraulic cylinders are used. The shelter configuration developed requires that the cylinders be placed close together on one axis. This arrangement multiplies the effect of any difference in the motion or forces associated with the actuators.

Three possible basic control methods have been considered:

1) Flow control - provide equal oil volume to each actuator.

2) Position control - use automatic control techniques to assure that position/time relationships of each cylinder are maintained.

3) Mechanical coupling for the actuator motions.

Combinations of these methods have also been considered.

Flow control to each cylinder has the disadvantage that most available flow control devices could result in up to 5 percent difference in flow to each cylinder. This would be equivalent to 5 feet of tilt on the prototype roof. The effects of this tilt on structural stability, load shift and actuator binding would require considerable analysis. The possibility of using coupled positive displacement pumps could reduce the error to an estimated 2 percent but the high quality pumps required would add significantly to the system cost (comparable to the servo controlled systems). The operation of this concept in a one actuator out condition presents a problem that has not been resolved during the study. This approach can be evaluated during further development of the shelter concept. If the problems associated with tilt of the roof and failure modes can be overcome, the concept would be cost effective.

One possible approach has been developed which would make the flow control concept workable. This is to provide a mechanical system to insure equal motion between adjacent cylinders on the critical axis and to utilize flow control devices on the non-critical axis. This approach would simplify the hydraulic system significantly, but would require some additional mechanical hardware. The concept could be applied to the model without difficulty; however, adapting the concept to the prototype has proved difficult.

An additional method to synchronize the cylinder motions is to utilize coupled master cylinders having volume equal to the actuators. This method is straightforward and would provide positive synchronization of the cylinders; however, the space requirements would be large and cost for equipment would be high.

Position controls were selected since a conservative design can be achieved with state-of-the-art design methods.

The basic power sources which have been considered are:

1) Electric Motor Driven Pumps

2) Diesel/Generator Driven Pumps

3) Direct Diesel Driven Pumps

4) Gas Generators

The additional possibility of using gas compressors and high pressure gas storage was quickly eliminated as neither compressors nor storage vessels of the required size are available.

The use of electric motors is dependent on the base design and an assumption was made that the shelter should be self-powered because of the large amounts of power required periodically for a short time. The option to use external electric power always exists.

Evaluation of the cost and space requirements for an engine/generator/motor power source suggests that direct engine driven pumping units would be more cost effective. This has been verified by discussion with vendors and has been selected as the prototype power system.

The gas generator power source can be considered for the hydraulic accumulator systems. This approach has not been evaluated fully since some development may be required for suitable gas generators and accumulators.

4. AIRCRAFT FLOOR ACTUATION SYSTEM

The elevator system for the prototype has not been studied in the same depth as the ceiling system.

The elevator system consists of an elevator platform which rests on interface pads on the foundation and which is guided during actuation by a guide rail system on the facility wall. The elevator will be provided with latching devices in the raised position to insure adequate support as the aircraft taxis on or off the platform.

The actuation system shown uses three multiple stage (five stage) telescoping hydraulic cylinders placed in wells in the foundation. The telescoping cylinders would be controlled by servo valves to maintain control when the load distribution changes. The elevator system actuation has been defined as hydraulic to be compatible with the cover concept; however, the elevator actuation may be accomplished by other systems including chain, cable, and screw actuators. Further trade studies will be necessary to identify the most suitable system.

The elevator actuation system would consist of the following major components:

Elevator Actuators - five stage single acting hydraulic cylinders

Two Rear Actuators

Stage 1	working diameter	0.254 m (10 in)
2	working diameter	0.229 m (9 in)
3	working diameter	0.203 m (8 in)
4	working diameter	0.178 m (7 in)
5	working diameter	0.142 m (6 in)

Total Working Stroke	7.32 m (288 in)
Overall Length Retracted	2.03 m (80 in)
Load Capacity Max. Working	196,000 N (44,000 lb)
Maximum Working Pressure	1100 N/cm^2 (1600 psi)

Forward Actuator

Stage 1	working diameter	0.318 m (12.5 in)
2	working diameter	0.292 m (11.5 in)
3	working diameter	0.267 m (10.5 in)
4	working diameter	0.241 m (9.5 in)
5	working diameter	0.216 m (8.5 in)

Total Working Stroke	7.32 m (288 in)
Overall Length Retracted	2.03 m (80 in)
Load Capacity Max. Working	392,000 N (88,000 lb)
Maximum Working Pressure	1100 N/cm^2 (1600 psi)

Pumps = two fixed delivery positive displacement pumps

Capacity: 303 l/min (80 gal/min)

Maximum Working Pressure: 1100 N/cm^2 (1600 psi)

Power: 56 KW (75 HP) from gearbox

Valves - three electro hydraulic servo valves

Capacity: 303 l/min @ 104 N/cm^2 (80 gal/min at 150 psi) pressure drop

Maximum Working Pressure: 1100 N/cm^2 (1600 psi)

Controls - the elevator control system will be a position feedback servo valve controlled system.

5. BUILDING LAYOUT AND EQUIPMENT INSTALLATION

Figure 12 shows the equipment layout on the first and second levels. Any equipment layout is considered tentative, but these layouts do illustrate what is possible.

The building is divided into three areas (the hangar area, equipment area, and the living and operations area). The equipment area, a noise source, is separated from the living and operations area by two 0.61 m (2 ft) walls. The hangar area is separated from both other areas by the 0.61 m (2 ft) wall. The equipment area and personnel and operations area are each divided into two levels. The upper level (65 m^2, 700 ft^2) of the equipment area houses all of the facilities support equipment. Equipment installed on the upper level of the equipment area includes the power source for the actuation systems, the heating and ventilating equipment, the emergency power system, a halon fire extinguishing system, and a survival ventilation system including CBR filtration for post attack operations. The lower level (73 m^2, 780 ft^2) houses aircraft support equipment and the hydraulic reservoirs for the roof and elevator actuation systems.

The operations area is on the second level above the personnel area. This area includes communications and office space. This area is underutilized and could be put to other uses such as additional personnel space.

The personnel area provides living quarters and facilities for eight men. The volume provided is 254 m^3 (8970 ft^3) or 32 m^3 per man (1120 ft^3/man). This is above most minimum standards for survival and habitability. If the operations and personnel quarters are combined in the upper level (one room 65 m^2), the lower level would be available for storage and shop space.

Ventilation for the facility would be through intake and exhaust blast valves and a blast attenuating delay duct system.

Air flow requirements are estimated to be 6000 to 10,000 CFM to provide space ventilation, equipment cooling, and operation of aircraft ground support equipment. This approximate air quantity is minimum for

NOTE:

Figure 12 is an oversize illustration that is located in Appendix "A" as drawing number HAS-P-001, Sheet 2.

Figure 12 Shelter Layout

normal operations assuming the installation is designed to explosion proof standards which would be required if the National Electrical Code is applicable. For these air quantities, a 3 foot diameter blast valve would be adequate.

The roof power system exhaust and cooling provisions will be separate from the facility ventilation and cooling system.

The installation of the equipment in the facility is not considered to be a major problem. Much of the installation including the actuators, piping and containers for hydraulic fluid, fuel, and coolant are inherently capable of being hard mounted for the criteria to be used. Other equipment such as controls and some components of the engine and servo systems will require shock attenuation to assure survival. For a minimum cost prototype the use of existing available equipment is desirable. The baseline concept is defined as having the power unit assemblies consisting of engine, pumps, gear box, and valving mounted on isolated base frames.

Piping and electrical interfaces with the shock mounted components will require flexible connection. The use of servo pumps will place all shock sensitive hydraulic components as the isolated assembly, and there will be two flexible connections to the piping for each actuator. The elevator servo valves would be similarly isolated on the frame.

The major weapons effects problem for the actuation system is the interface between the actuator and the ceiling. This interface must accommodate the relative motion between the actuator, which is rigidly attached to the walls, and the ceiling which will move up to 50 mm (2 in) horizontally and 25 mm (1 in) vertically with respect to the walls.

A fixed interface would require that the actuators restrain the ceiling during ground shock. This is not considered feasible.

The actuator is therefore not rigidly attached to the ceiling, but is provided with clearance for horizontal and vertical down motions of the ceiling. Vertical up relative motion is accommodated by an elastomeric pad and by compressibility of the oil in the actuator.

The interface during ceiling lifting is through an additional elastomeric pad which allows limited rotational and translational relative motion to accommodate actuator displacement differentials and misalignments due to installation and blast damage.

In addition to the major components shown on the drawing, the power unit installation will include additional equipment for fuel supply, engine cooling and exhaust. Engine cooling for this limited operation system can be accomplished by air cooling, stored liquid coolant, or ebullient cooling.

The minimum space requirement is achieved with the ebullient cooling method. Engine cooling is accomplished with a coolant loop which has a boiling heat exchanger, and the steam generated is vented to atmosphere. This method would require approximately 95 liters (25 gallons) of water per closure operating cycle.

A stored coolant system would have minimum complexity and would require approximately 950 liters (250 gallons) of water per operating cycle which would heat to approximately 93 degrees C (200 degrees F). Water would be cooled between operating cycles by circulating through a low capacity heat exchanger in an air stream or embedded in the facility wall. The ebullient cooling method is proposed for the prototype shelter.

The engine exhaust system will require venting to atmosphere. This would be accomplished by directly venting through a discharge pipe and a blast attenuating system which will limit the blast pressure delivered to the engine to an acceptable value, and which will either remain open or be self-opening after a blast event.

Hydraulic fluid storage - the actuation of the ceiling and the elevator will require approximately 7600 liters (2,000 gallons) of hydraulic fluid. Additional fluid is required for filling piping, leakage, etc., and a storage capacity of 9500 liters (2,500 gallons) is provided. The hydraulic fluid is stored in four hard mounted cylindrical tanks in the lower equipment room.

6. DESCRIPTION OF PROTOTYPE

Figures 13 and 14 illustrate the prototype shelter. The building is a reinforced concrete structure with exterior dimensions of 24.4 m X 25.4 m X 9.1 m (80 ft X 83.3 ft X 29.9 ft). The key feature of the building is the roof which may be elevated to allow aircraft access. When the roof is in the elevated position, the aircraft may taxi between the roof actuators onto an elevator floor. Then the elevator floor lowers the aircraft into the shelter so that the roof can be lowered to provide protection from weapons effects. Aircraft egress follows the reverse procedure. The roof is elevated followed by the aircraft elevator so that the aircraft may taxi. Short span kickplates are provided on the elevator floor to bridge the gap of the roof sill.

This vertical access allows fixed columns and bearing walls to be sited next to the aircraft fuselage. This reduces the roof span to 8 m (26 ft) between support points. The bearing walls provide interior shear panels which help reinforce the exterior walls in the forward part of the building (forward, aft, etc., descriptive terms are using the aircraft as a reference point). The walls in the aft part of the building resist loads from the soil with both a horizontal span and a cantilevered span from the foundation.

Both the elevator and the roof actuators are partially recessed within pits in the foundation. The elevator floor is recessed into the foundation so that the top is flush with the first level floor. The forward part of the shelter is broken up into four rooms by the bearing walls and second level floors.

7. ACTUATION SYSTEM OPERATION/CONTROL

The system would lift the ceiling on command at a constant rate to the maximum height. The nominal lift time is 3 minutes.

Control system - the operation of the ceiling and elevator systems will use a servo control system where the position of each actuator is monitored and the output of the variable delivery pumps or the servo valves is controlled to maintain the desired motion of the ceiling cover or elevator. The functions and capabilities of the control system for the prototype will be very similar to the model system described on the drawing.

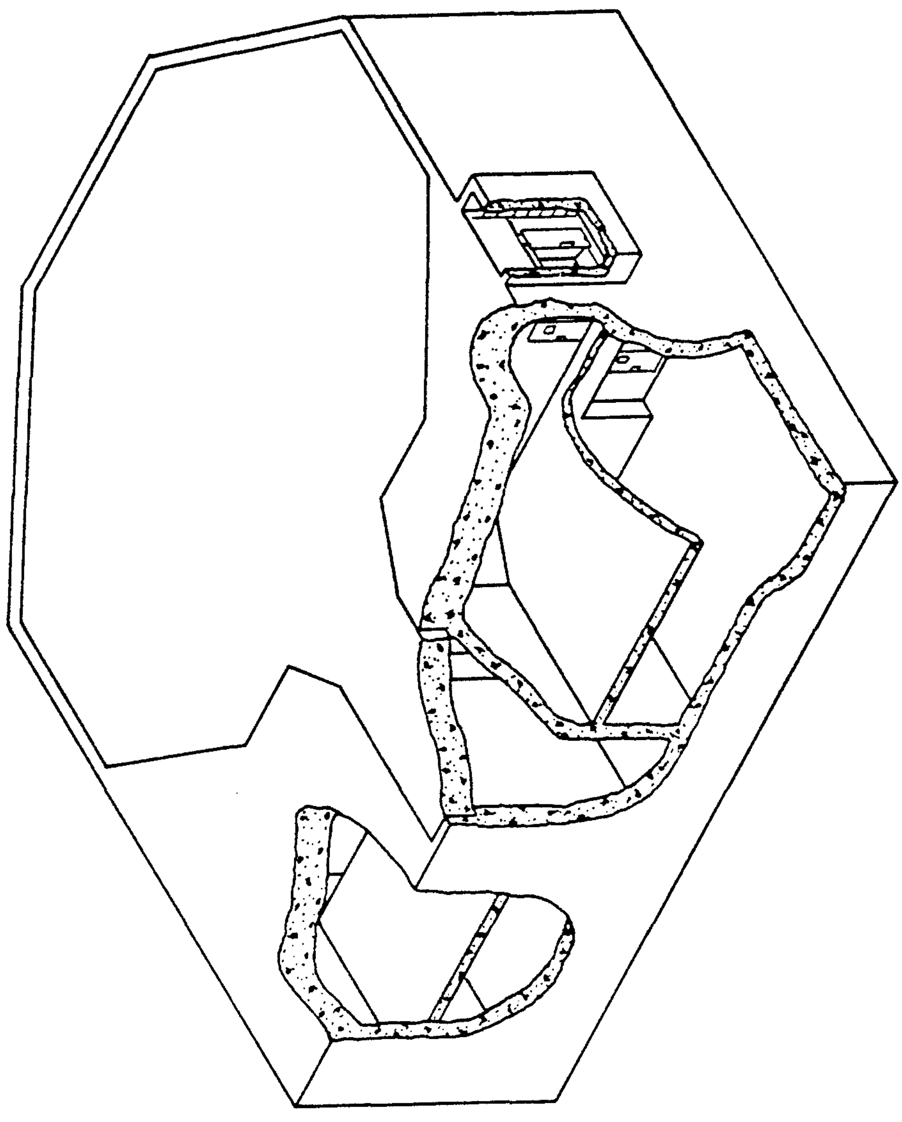
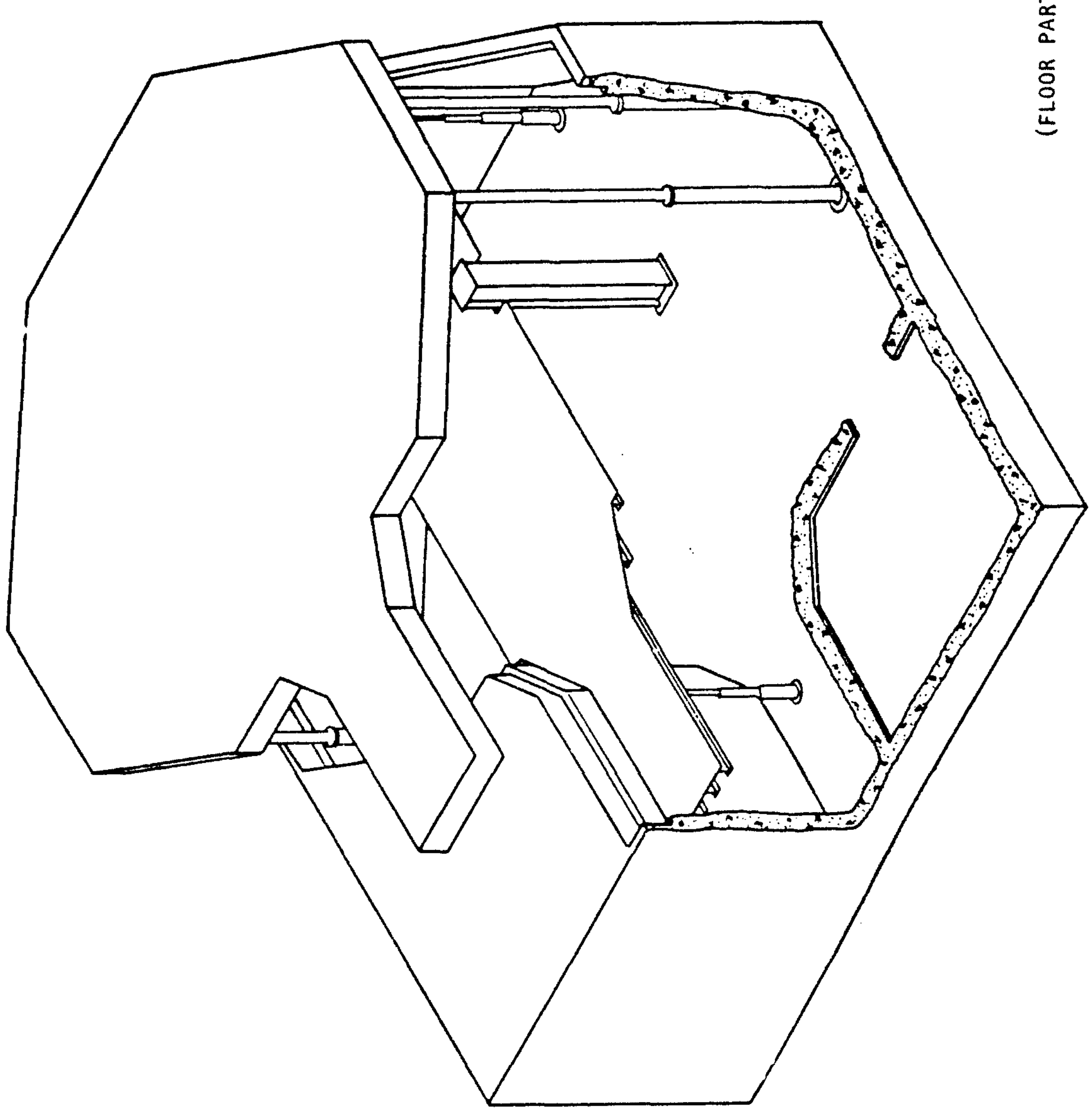


Figure 13 Hard Flush Aircraft Shelter - Closed Mode



(FLOOR PARTLY RAISED)

Figure 14 Hard Flush Aircraft Shelter - Open Mode

The ceiling will be hydraulically locked for normal operations where the ceiling would not be in the raised position for extended time periods. A mechanical locking device would be provided to support the ceiling in the up position for extended periods.

The three minute lift cycle does not include diesel engine starting. It is assumed that the power system has been activated and the engines are at a suitable temperature before attempting to raise the ceiling.

For a one actuator out condition, the inactive actuator would be bypassed by manual valves, and the control system would be in an emergency mode where the rate command would be at one-half of the normal velocity of 1.6 in/sec. This is necessary to keep the power requirements constant.

Elevator operation - the elevator system will also operate at a fixed rate and can be raised with the ceiling or independently when the ceiling is in the raised position.

The elevator can be provided with mechanical latching devices in the raised position to provide positive safety and to transfer the varying loads to the wall structure as the aircraft taxis on or off the platform.

The ceiling and elevator actuation systems are shown schematically on Figure 11, and the arrangement of the equipment in the facility is shown on Figure 12.

8. COST CRITICAL ITEMS

The major cost critical item is the moveable roof. A weight savings in the roof directly reduces the cost of the actuation system and may reduce the cost of the roof structure itself. With the roof opening time set at 3 minutes, a weight saving in the roof will lead to a horsepower reduction in the power source, thereby reducing costs.

The roof actuation system itself is the next significant cost item. The concept trade is a sliding versus lifting type of system. A hydraulic lift system was chosen because of the availability of standard designs and off-the-shelf components and because it reduces the total vulnerable target area (a sliding roof would require tracks more vulnerable to weapons effects).

The power source for both actuation systems is a critical item for which there are many alternatives. Direct drive diesels were chosen because of low first cost and low development cost, reliability, size and independence from outside utility support.

Most of the remaining costs are in the structure. This cost can be considered distributed equally throughout the structure with no particular element being more critical than any other.

9. ADAPTABILITY TO MULTIPLE PARKING

Figures 15, 16, and 17 show a concept shelter for two aircraft. Conceptually, this is still the Boeing hard flush shelter with a moveable roof, vertical access, and intermediate supports.

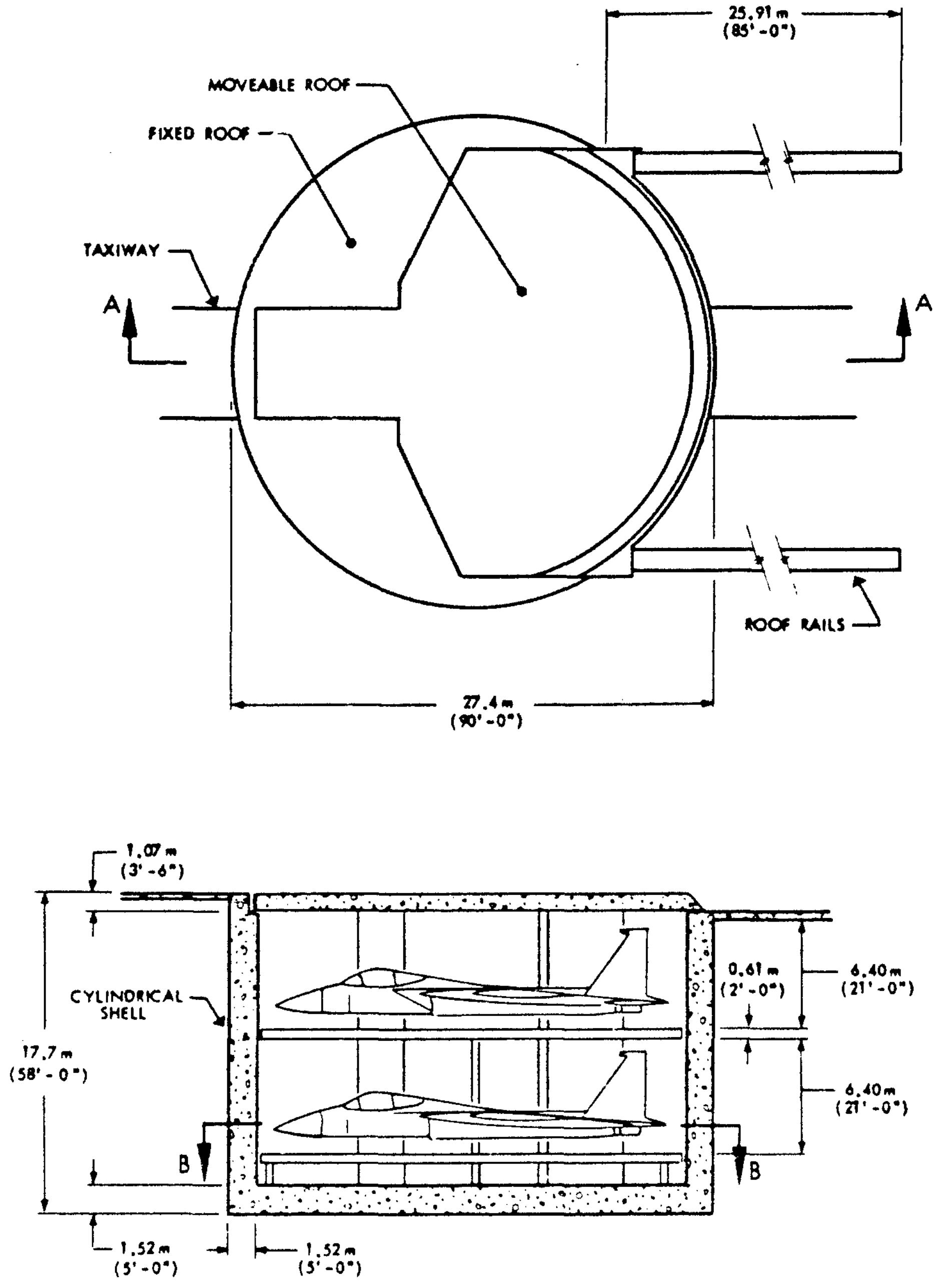
A sliding roof (see Section IV, paragraph 3.b) is shown because there are no existing standard design hydraulic actuators with the vertical stroke required for a vertical lift roof. For the same reason, a cable lift system is used for the aircraft elevator system. The columns are replaced by bearing walls for greater stability. This concept uses a silo for the walls, since the cantilever action from the base is not very effective. A silo type wall system also could be used for the baseline system.

There are several floors available for equipment and personnel space.

This two aircraft shelter concept has minimal cost advantage per aircraft over the baseline concept.

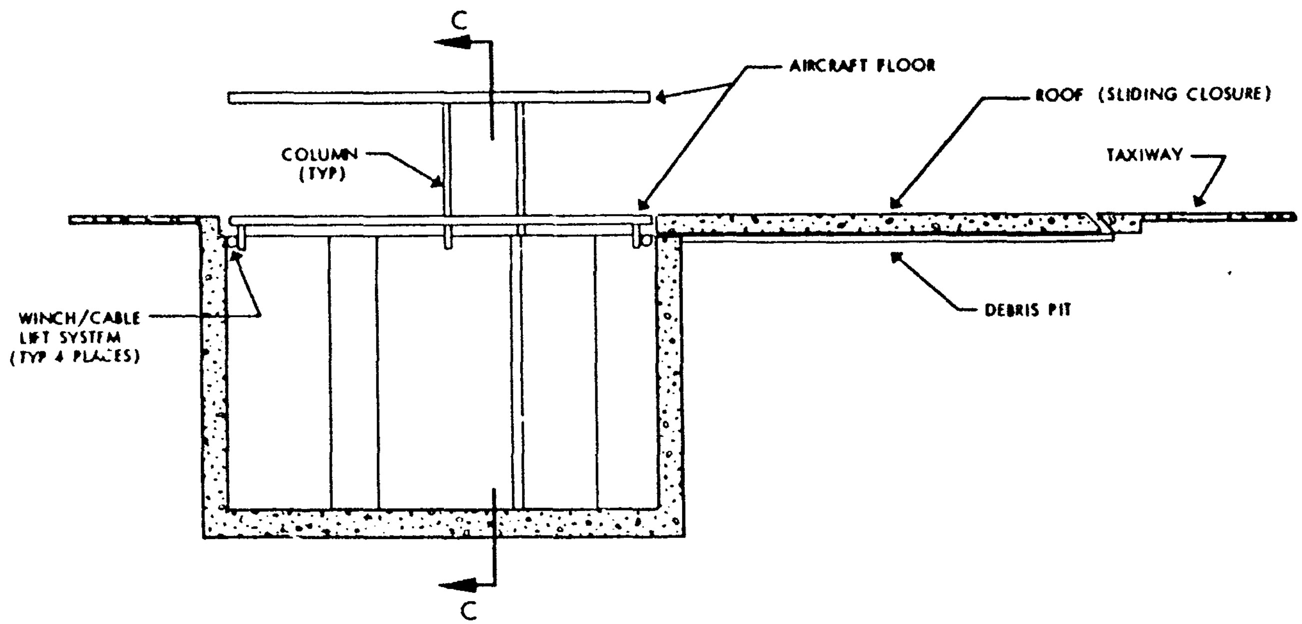
10. INSIDE ENGINE STARTUP OPTION

The ability to discharge the aircraft in minimum time from the shelter requires that the aircraft engines be started at the earliest possible time. It would be desirable to start the engine within the shelter if possible. The problems associated with starting of the largest proposed aircraft (F111-F) have been evaluated on a preliminary basis. The idle mass flow of the F111-F engines is about 50 kg/sec (110 lb/sec) and the discharge temperature is about 316 degress C (600 degrees F). This equates to more than 5100 m^3/min (180,000 ft^3/min) at 316 degrees C (600 degrees F) in a closed shelter. This flow of gas would cause rapid temperature rise and risk of harm to personnel and damage to the engines as exhaust is recirculated. It is possible to provide a ventilation system to provide this mass flow;



ROOF CLOSED-FLOOR LOWERED
SECTION A-A

Figure 15 Multiple Parking Concept - Roof Closed, Floor Lowered



ROOF OPEN - FLOOR ELEVATED
SECTION A-A

Figure 16 Multiple Parking Concept - Roof Open, Floor Elevated

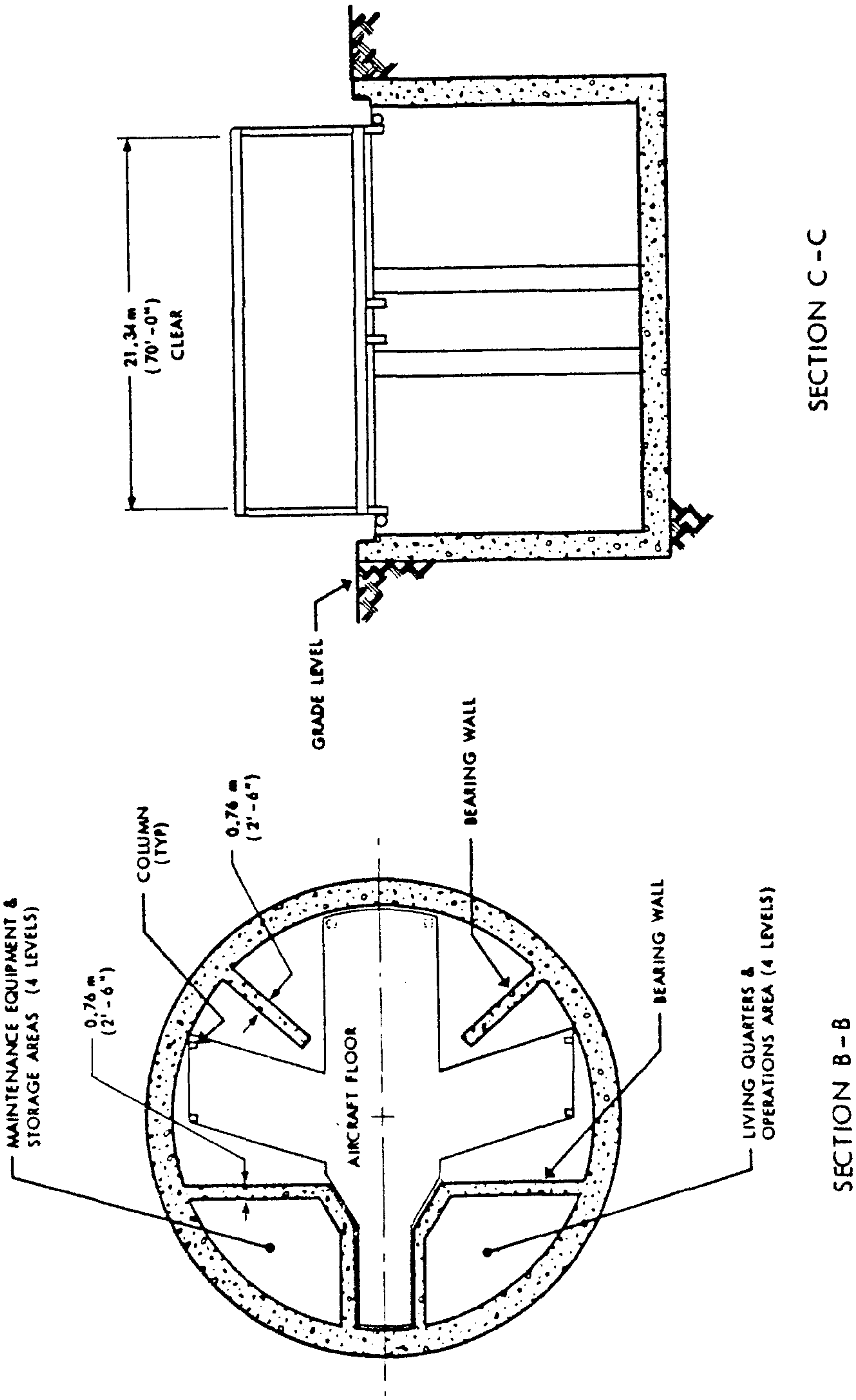


Figure 17 Multiple Parking Concept - Section Views

however, the size of components and power requirements would be excessive (approximately 1.8 m (6 ft) diameter. Blast valves and two 373 KW (500HP) fans required). The possibility of providing a less positive air flow could be evaluated for small aircraft; however, even at 50 percent of this flow, the recirculation temperature could be damaging to the aircraft within a short time.

Since it is probable that the aircraft can complete the startup cycle within 2 minutes, it is considered reasonable to initiate engine startup sometime after the cover opening begins. The availability of fresh air at this time would prevent excessive temperature buildup, and the aircraft would be prepared to taxi when the elevator reached ground level. An exhaust diverter could be provided to further control recirculation if required. A potential problem exists with debris falling into the shelter; however, this is considered a solvable problem and should not affect the egress time.

It will be necessary to further evaluate the tolerance of the aircraft to this type of operation with the cooperation of the manufacturer and the users.

SECTION V

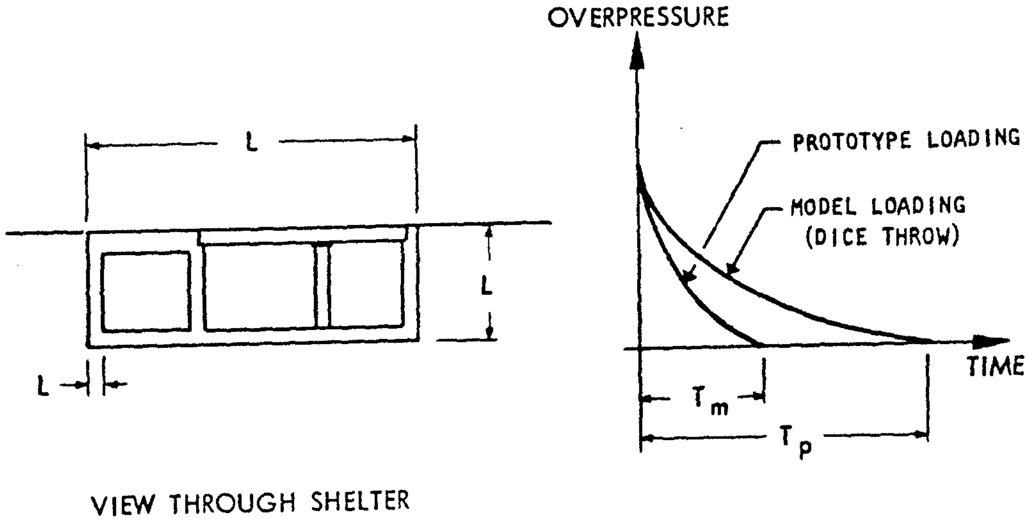
MODEL SHELTER

The model shelter is a 1/3 scale structural replica of the prototype shelter. The model drawings and prototype drawings for comparison are shown in Appendices A and B. The design approach followed was to first determine the interior dimensions of the prototype shelter by laying out aircraft, equipment and personnel areas. Then the dimensions were scaled down (X 1/3). The model structural sections were sized in detail for the Dice Throw overpressure time history. The sections were scaled up to the prototype dimensions to insure that the sections were practical on a prototype scale. Structural elements which were impulse sensitive were analyzed for the prototype overpressure time history in order to determine structural adequacy on the prototype scale. The model shelter mechanical system was designed to follow the favored concept for the prototype system. The result is a final design for the model and a good preliminary design for the prototype.

1. MODEL SCALE

Figure 18 shows the scaling rules followed in this effort. The results of the overpressure from a 4.2 (10^{12}) J (1 kT) yield on the model will directly scale to the effects of a 1.1 (10^{14}) J (27 kT) yield on the prototype.

Almost all of the structural elements were scaled dimensionally. Where shapes were used in the model and exact dimensional scaling was not practical, frequency scaling was used. Table 3 lists the structural elements and their scaling parameters. Strength, materials, and density were scaled one to one. Concrete clearance (distance from concrete surface to edge of reinforcing bar) was approximately scaled. The model concrete clearance is 19 mm (3/4 in). The scaled prototype concrete clearance would be 57 mm (2-1/4 in), which is greater than the ACI code requires in most cases.



$$n = \frac{L_p}{L_m} = \frac{T_p}{T_m} = \frac{\omega_p}{\omega_m} = \frac{\delta_p}{\delta_m} = \frac{A_p}{A_m} = 3$$

$$V_m = V_p, \quad \rho_m = \rho_p, \quad E_m = E_p, \quad \sigma_m = \sigma_p, \quad \varepsilon_m = \varepsilon_p$$

A = ACCELERATION
E = YOUNG'S MODULUS
L = LENGTH
n = SCALE FACTOR
T = TIME
V =
SUBSCRIPT $_m$ = MODEL
SUBSCRIPT $_p$ = PROTOTPYE

δ = DISPLACEMENT
ε = STRAIN
ρ = DENSITY
σ = STRESS
ω = FREQUENCY

Figure 18. Scaling Laws

TABLE 3

SCALED STRUCTURAL ELEMENTS

(S.I. UNITS)

ELEMENT MODEL (PROTOTYPE)	THICKNESS* (m)	A_S* (%)	FREQUENCY* (HZ)	UNIFORM* PRESSURE AT COLLAPSE (N/cm^2)
Fixed Ceiling	0.508 (1.52)	0.367 (0.416)	340	235 (267)
Front Wall	0.203 (0.610)	0.258 (0.278)	559	47.9 (51.5)
Rear Wall	0.254 (0.762)	0.658 (0.625)	105	38.6 (36.6)
Interior Wall	0.203 (0.610)	0.323 (0.347)	---	---
Foundation	0.508 (1.52)	0.250 (0.250)	---	157 (149)
Columns	---	0.045 (0.361)	168 (54.9)	
Elevator Floor			17.4 (5.4)	
Primary Actuators			42.1 (17.6)	
Fixed INT. Floor	0.102 (.305)	0.408 (0.458)	82.0	9.7 (10.2)
Moveable Roof	0.362 (1.09)	1.75 (1.75)	104 (35) Rigid Body Mode on Flex. Pads	154 (154)

*Prototype Units in Parentheses.

The moveable roof is supported by a neoprene seal and bearing pad combination which sits on the walls and the columns. The model neoprene bearing pads were sized to meet a load/deflection curve. The load/deflection curve was determined from the frequency of the roof (idealized as a rigid body) setting on the neoprene pads (flexible spring). This frequency was determined by scaling the frequency of the prototype shelter roof on its neoprene pads. This type scaling was necessary for design because the neoprene load/deflection characteristics are non-linear and strain rate dependent.

The strain rate for the model is three times the strain rate of the prototype shelter. The yield stress and ultimate stress of steel and concrete increase with strain rate. The effect of strain rate was compared for the fixed roof and the moveable roof between the model shelter and the prototype shelter. The model fixed roof will be 10 percent stronger than the prototype fixed roof due to strain rate effect. The model moveable roof will be 5 percent stronger than the prototype moveable roof. Since these differences are within the normal variation of material mechanical properties, they are not considered to be an unreasonable source for error.

2. TEST PECULIAR DESIGN ITEMS

There are a variety of items which are common to both the model and the prototype, but have no accurate scale. Table 4 lists some of these and reflects appropriate comments.

The foundation has several pits and trenches for actuators and piping. These affect the structural integrity of the foundation. Their size is based on the hydraulic system space requirement. To date, the prototype design is not far enough along for a close comparison with the model actuator pits, but it appears that the pits in the model are proportionally larger than the prototype pits. The elevator floor in the prototype shelter will be recessed into the foundation; therefore, the wall on either side of the elevator will have a proportionally shorter cantilever span (prototype). This implies that the prototype shelter will have a stronger and stiffer foundation than the model. Offsetting this to some degree is the soil below the foundation in the Dice Throw Test bed. This soil is stiffer than a

TABLE 4

DETAILS NOT SCALED (ACCURATELY)

ELEMENT	COMMENT
Actuator pits in foundation	Sized for installation of actuator, proportionally larger in model than in prototype
Rubber seal outside bearing pad	Sized for tolerance between walls and ceiling
Roof tie downs	Sized for load and ease of instrumentation
Anchorage	Sized for load with typical construction detail
Hydraulic power unit, valves, control system	Sized for model function

minimum type soil (such as silty sand) so the pressure distribution results in lower bending moments in the foundation.

The design approach for seals and anchorage is the same for prototype and model shelters. However, since these details have not been determined for the prototype, the scale between model and prototype is not known.

The test results will provide data on the rebound loads from the moveable roof to the roof tie downs. The prototype latch system will be automatic in order to minimize roof opening times. The model tie down system is designed to be easily instrumented, so data can be accurately taken. The roof tie downs were sized, based on a rigidly supported foundation. This results in worst case rebound loads on the tie bars. The predictions using the Dice Throw site soil data (flexible support for the foundation) indicate that the foundation is responding downward, thereby reducing the rebound loads. If sufficient damping exists on the roof and bearing pads, roof rebound will not load the tie bars.

The design approach for selecting the clearances for the model moveable roof and elevator floor is the same approach for the prototype. The permanent distortion of the walls due to overpressure loading poses a design problem which must be solved to avoid interference between the roof and walls after an attack.

The model hydraulic supply system is shock isolated since some of the components have not been qualified for any shock level. If practical, prototype hydraulic components shall be qualified for shock and hard mounted. Response data from the Dice Throw model can be used to determine the required qualification for shock.

The model shelter mechanical systems were designed to be functionally similar to the proposed prototype design. However, some mechanical components are not true structural models, since available hardware had to be selected. The major differences between the model installation and the prototype design are as follows:

1) The ceiling actuators are solid shaft, tie rod type, high pressure cylinders where the prototype actuators would be fabricated of centrifugally cast hollow steel cylinders without tie rods.

2) A constant pressure hydraulic power source, electrically driven, is used in conjunction with servo controlled valves for the model where the prototype system would have engine-driven variable displacement servo controlled pumps. In addition, the pumping unit is located in the center of the model shelter for accessibility, rather than in the space designated for equipment in the prototype.

3) The elevator cylinders are three stage, commercially available telescoping cylinders which are oversize in both stroke and diameter, rather than the five stage telescoping cylinders proposed for the prototype shelter.

4) Locking devices on the ceiling actuators, latching devices to restrain the ceiling, and latching devices for the elevator in the raised position have not been provided on the model. The model ceiling is restrained by fixed turnbuckles which perform the same function as the prototype ceiling latches.

5) The hydraulic components have been located within the main room of the model and installed on shock isolated plates, where the prototype equipment would be mounted on isolated platforms in the equipment space. The prototype floor area would be free of complex piping installations.

Two key functional features for this shelter concept are provided for the model similar to the proposed prototype design:

1) The interface between the ceiling actuators and the ceiling in the retracted position provides freedom for horizontal and vertical relative motion between the ceiling and the walls. Without this freedom, the actuators would be required to restrain the motion of the ceiling which is not considered desirable. In addition, it is necessary to provide for misalignment of actuators due to installation tolerances or blast damage.

2) The motion of the ceiling is controlled by a position feedback servo system. This method has been provided for the prototype system as a positive means of controlling the motion of the large slab and allowing for operation with one actuator out.

3. DESIGN CRITERIA

The criteria for the structure is based on the ACI Code (1971) as a code of practice. A safety factor (load factor) of one is used for the test effects. The construction factor (ϕ) is 1.0, rather than 0.85 as the code recommends. Reinforcing bar clearances for concrete against soil are not adhered to. The ACI practice for shearhead design was not adhered to since the ACI practice applies to conventional reinforced concrete. The shearhead in the moveable roof is a composite steel plate and concrete section, so the shearhead was sized by apportioning load to the steel and the concrete (i.e., the limit $v \leq 5\sqrt{f'c}$ was not adhered to).

The structural allowables for the model are given in Table 5. The allowables for the prototype shelter would be quite similar. If necessary, the allowable ductility ratios for the final prototype design could be increased.

TABLE 5

STRUCTURAL DESIGN CRITERIA

MATERIAL		FLEXURE OR TENSION	SHEAR	COMP.	BOND	DIAGONAL TENSION
				STRESS		
Allowable Ductility Ratio μ						
Concrete		1.3	1.5	1.5	1.0	1.0 (unreinforced) 1.5 (reinforced)
Steel						
A615	GR40	3	3	3	---	---
	GR60	3	3	3	---	---
A36		3	3	3		
Allowable Stress						
Concrete		1.3f'c	0.25f'c	1.3f'c	OR ACI 318-71	$2.0(f'c)^{0.5}$ (unreinforced) $7.5(f'c)^{0.5}$ (reinforced)
Steel						
A615	GR40	1.25Ty	---	1.25Ty	---	---
	GR60	1.2Ty	---	1.2Ty	---	---
A36		1.25Ty	0.75Ty	1.25Ty	---	---

$$\mu = \frac{\text{Max. Deflection}}{\text{Deflection at Yield}}$$

f'c = 28 Day Compressive Strength

Ty = Static Tensile Stress at Yield

SECTION VI

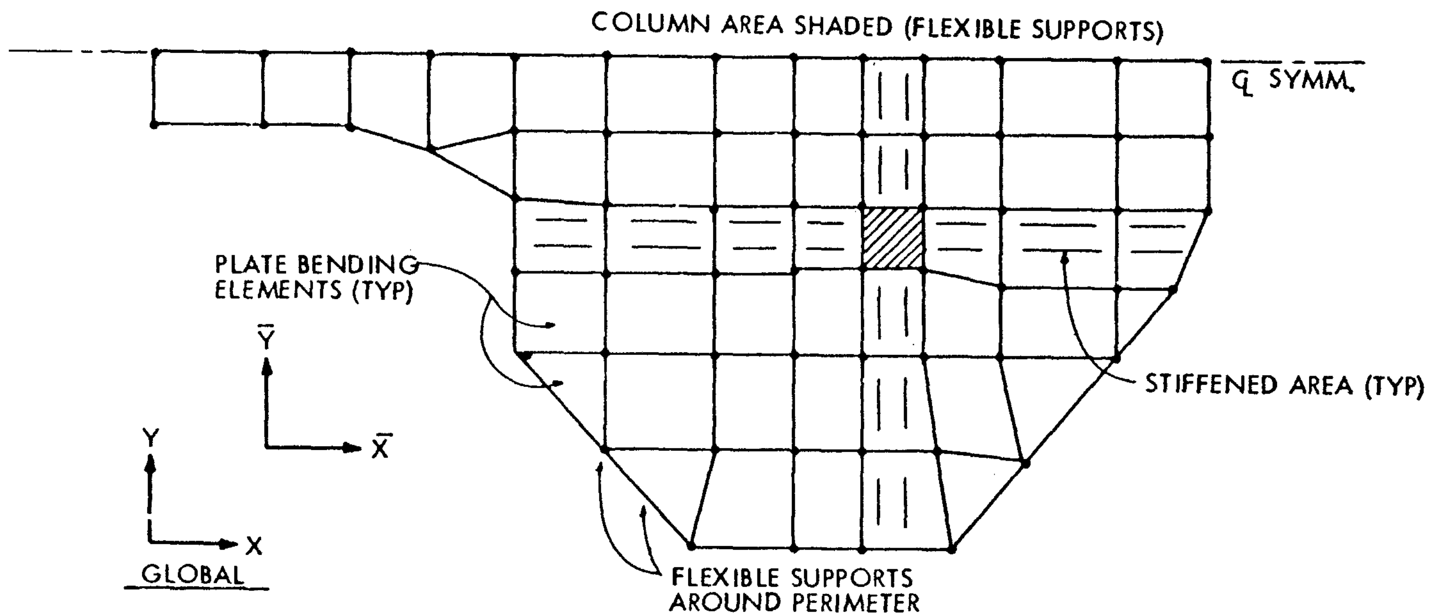
PREDICTIONS

Most of the measurement predictions are based on an extension of the analysis used for the model design. The roof and foundation idealizations were developed during the design effort, and the model drawings are based on results from those idealizations. The spring/mass idealization and wall idealization were developed toward the end of the design effort to verify assumptions made during design.

The roof idealization is shown on Figure 19. It is composed of plate bending elements supported by springs modeling the neoprene bearing pads, walls, and column. During rebound response, the tie downs are described by the flexible supports. Anisotropic elements are located at locations where the shearhead webs stiffened the composite section in one direction. The input loads are the pressure time history as the overpressure wave advances from rear to front of the shelter roof. Other loads including rebound loads are static pressure loads. The output is internal force distribution, mode shapes, frequencies, displacements, velocities and accelerations. Figures 20 to 24 show the first five mode shapes.

The foundation idealization is shown on Figure 25. It is composed of beam and plate elements supported by springs describing the soil stiffness. The loads are static loads applied through the walls and columns. The distribution of loads is based on the results from the roof idealization and the time phasing is from the spring/mass idealization. The soil stiffness was varied at each time (static load case) to account for the effect of the soil stress wave propagating downward from the foundation. The rigid body displacement of the walls matches the displacement X_4 in the spring/mass idealization (see Figure 27). Output is forces, displacements, and soil pressures.

Figure 26 shows the rear wall idealization. This idealization was developed to determine the combined action of the rear and side walls. The results verify that the critical collapse mechanism is a mechanism involving single wall panels. However, the fundamental frequency of the



LOADS: (1) ELEMENT PRESSURES (STATIC)
(2) JOINT LOAD/TIME HISTORY (DYNAMIC)

SUPPORTS: (1) WALLS, NEOPRENE PADS, & COLUMN
(2) REBOUND RESTRAINTS
(3) ACTUATORS

Figure 19. Roof Idealization

f_n = 60 cps

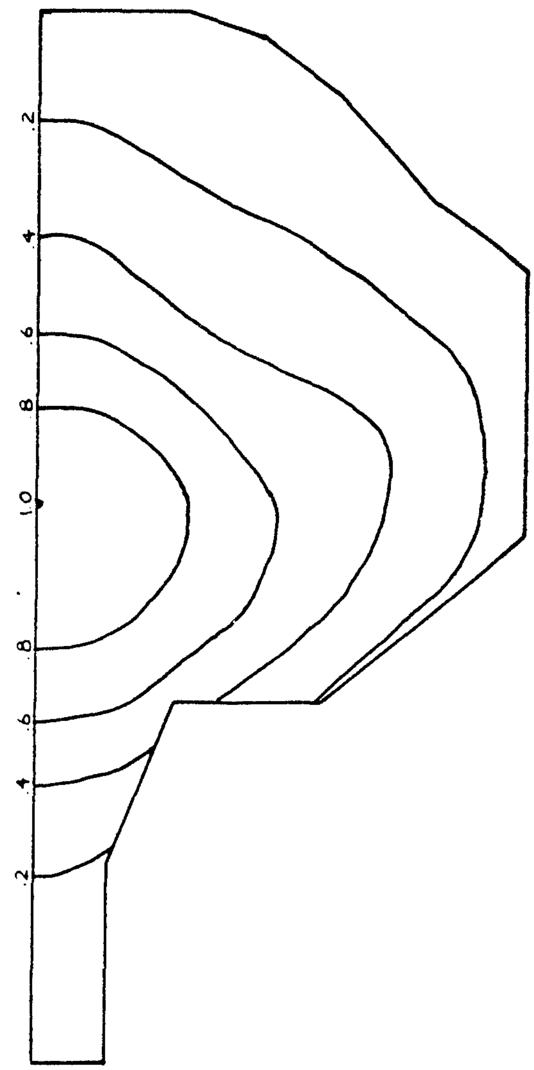


Figure 20. Mode 1

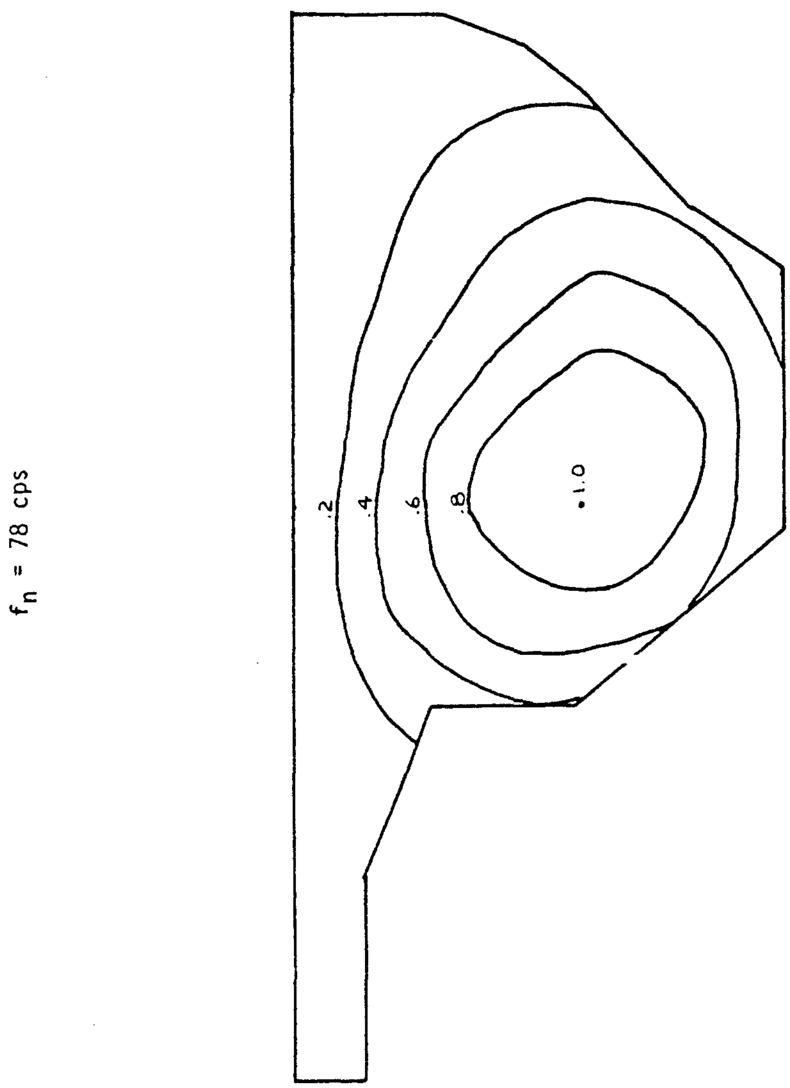


Figure 21. Axisymmetric Mode 1

f_n = 83 cps

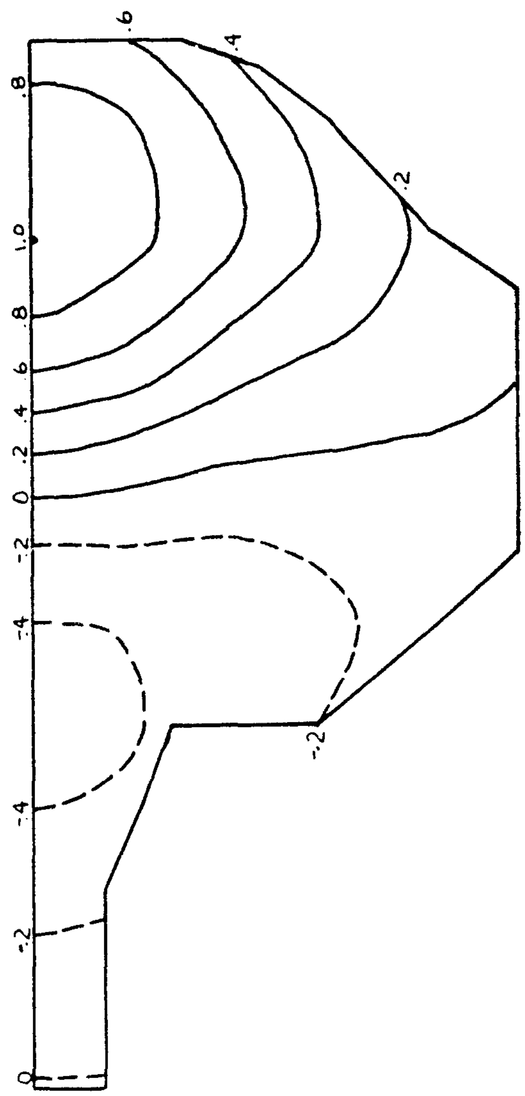


Figure 22. Mode 2

$f_n = 93$ cps

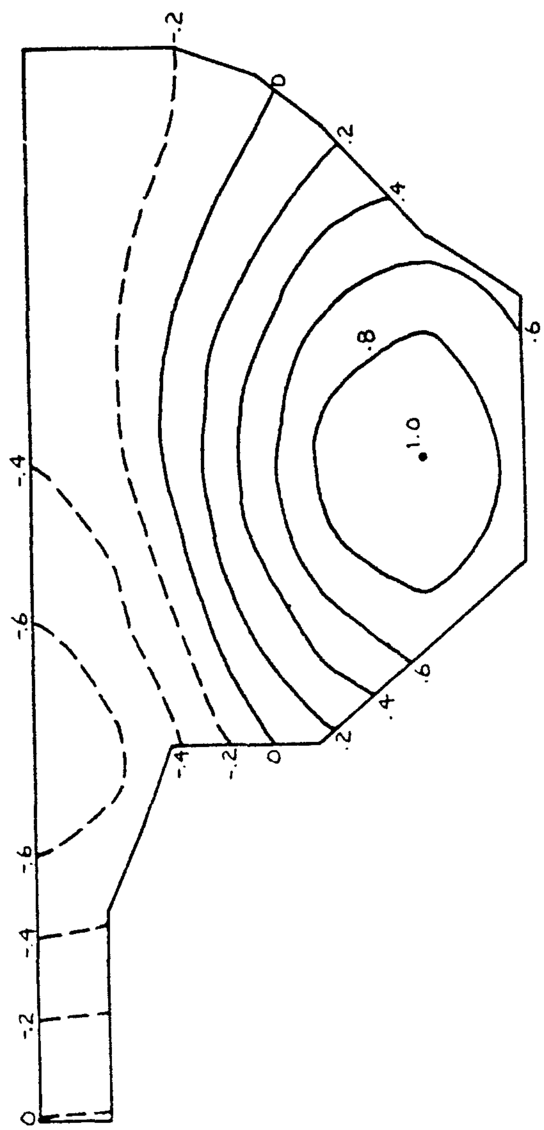


Figure 23. Mode 3

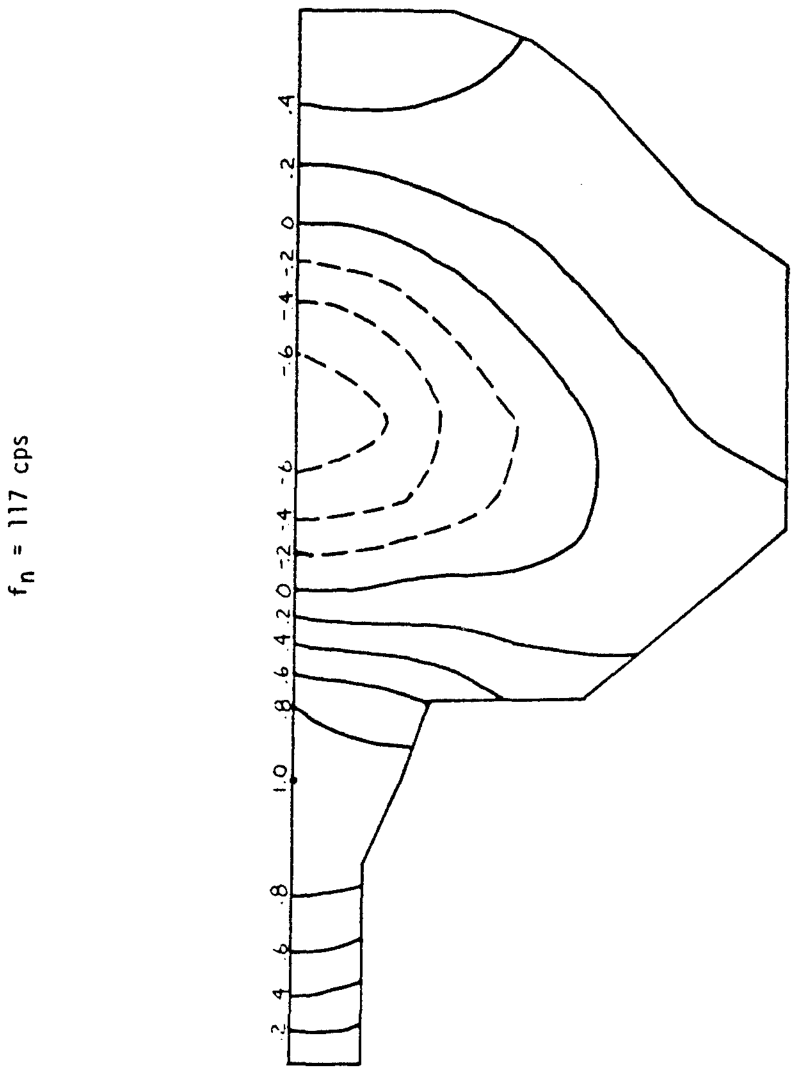
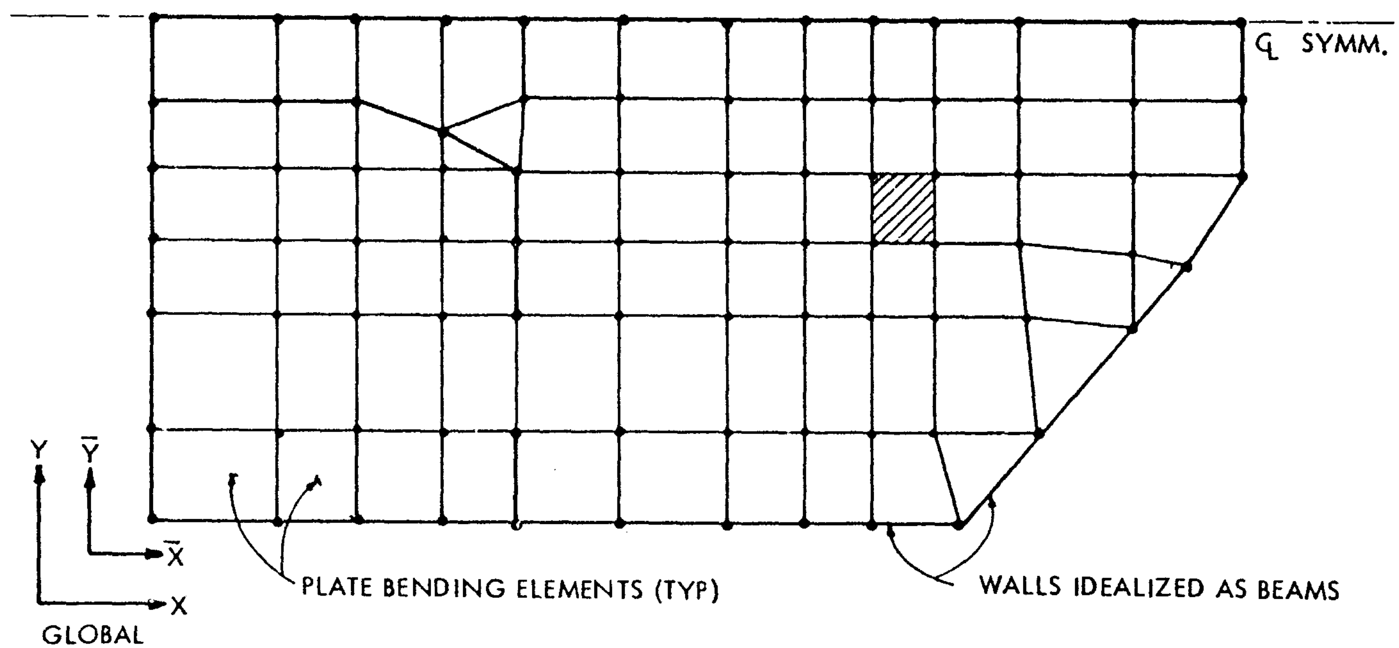


Figure 24. Mode 4



LOADS: STATIC LOADS APPLIED THROUGH WALLS & COLUMN REACTED BY SOIL SPRINGS UNDER EACH JOINT

Figure 25. Foundation Idealization

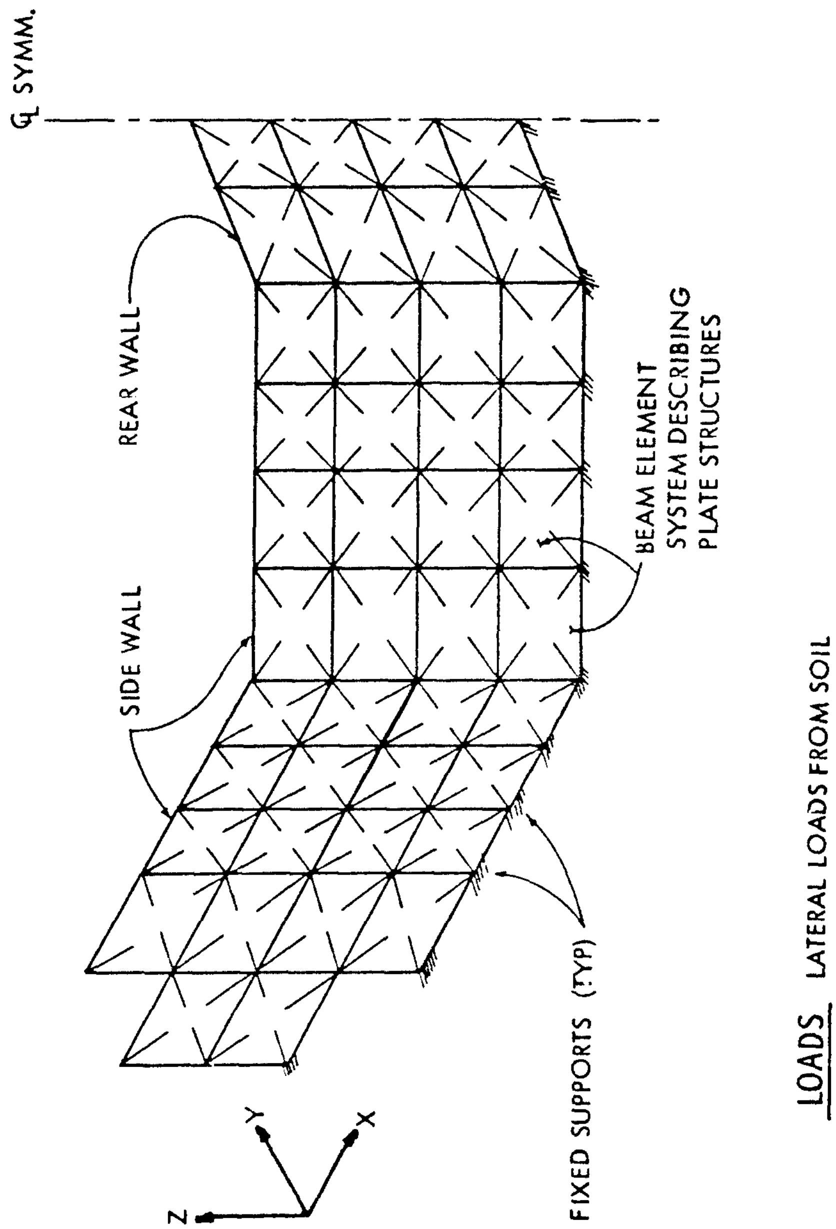


Figure 26. Wall Idealization

combined system is lower than the frequency of a single panel.

The force distribution in the finite element programs is based on linear elastic material mechanical properties. The mechanical properties used in the programs are shown in Table 6. Reinforced concrete section properties for the programs were based on the average of the cracked and uncracked sections.

TABLE 6

MECHANICAL PROPERTIES

Steel	Young's Modulus	= 20.7 (10^6) N/cm^2 (30,000 ksi)
	A36 Yield Stress	= 31,000 N/cm^2 (45 ksi)
	Reinforcing Bar Yield Stress	= 50,000 N/cm^2 (72 ksi)
Concrete:	Young's Modulus	= 2.5 (10^6) N/cm^2 (3600 ksi)
	Ultimate Strength	= 3580 N/cm^2 (5.2 ksi)

The force distribution results are used as the first estimate of the plastic collapse load for the slabs. The final collapse for the slabs was based on yield line theory using the least work approach.

The finite element idealizations were solved using the Strudl II program. The static program is the displacement (or stiffness) method of structural analysis. Both beam and plate elements were used. Eigenvalues are solved using an iterative technique. The response due to a force time history is based on a normal mode analysis.

The spring/mass idealization ties the various parts of the structure and soil together for vertical models. The foundation and roof idealization provided the structural characteristics input into the spring/mass idealization.

Figure 27 shows the idealization and a description of the non-linear springs between the masses. Each spring describes the frequency, yielding, and the stiffness of various components of the shelter. PCAV and K_4 describes the soil. K_4 is sized to describe the expected soil recovery (about 25 percent). PCAV represents most of the soil reaction. The input is force time history representing overpressure loads on the fixed and moveable roof masses. The output is force, displacement, velocities, and

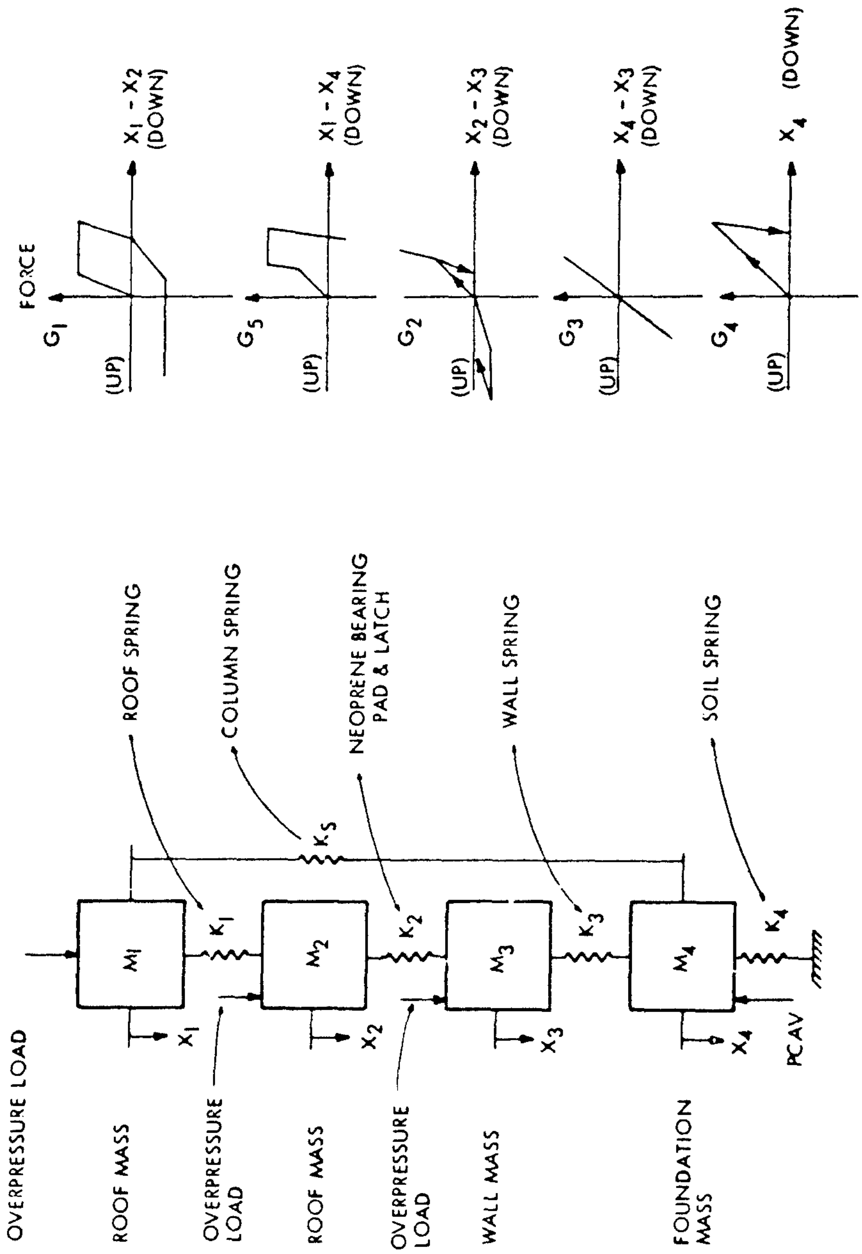


Figure 27. Shelter/Mass Idealization

acceleration time histories. The response of the spring/mass idealization is solved by stepwise numerical integration of the equations of motion.

Initial lateral interface pressures on the rear walls were based on the soil pressure induced in the uniaxial strain test until the wall responded to 5 mm (0.2 in), then the active pressure soil coefficient was used to determine the lateral pressure. The attenuation of the vertical soil pressure was determined following the procedure in paragraph 5.3.2 in Reference 1. The horizontal motions of the foundation, roof and interior floors were determined by the solution of equation 7-40 in Reference 1.

Soils data were provided informally through AFWL by the Waterways Experiment Station (WES). The data was for the German structures area at the Dice Throw Site. The nearest boring (S-4) was approximately 107 m (350 ft) from the Boeing shelter model. The data included uniaxial stress strain relations, shear stress envelopes, and subgrade reaction coefficients for caliche, deep sand, high density backfill, and low density backfill.

The predictions for the shelter model were based on a soil profile as follows: (1) surface down to 2.4 m (8 ft)-caliche; (2) below 2.4 m (8 ft) deep sand. Low density backfill was assumed for predictions. The backfill description is on Sheet 1 of the model drawings in the appendix. The large variation in the backfill strength properties can result in large variations in interface pressure at different wall locations. Table 7 summarizes the soil properties used in the predictions.

The analytical approach for each prediction is shown in Table 8. Since the results from one approach are used as a starting point for another approach, often two approaches are noted for one measurement prediction.

When an estimate is noted for a prediction; the prediction is based on judgment or results from other tests, rather than an analytical approach. Handbook approaches are based on Reference 1. The predictions are shown on Figures 28 to 40. Zero time is the time of arrival of the overpressure at the northeast wall. For measurement locations, see Section VII - Test Plan.

1. Crawford, R. E., et al, Air Force Manual for Design and Analysis of Hardened Structures, AFWL-TR-74-102, Air Force Weapons Laboratory, Kirtland Air Force Base, New Mexico, October 1974.

TABLE 7

SOIL PROPERTIES

Deep Sand:		
Compression modulus	-	27600 N/cm^2 (40,000 psi)
Compression wave velocity	-	429 m/s (1410 FPS)
Density	-	1.5 g/cc (93.6 PCF)
Caliche:		
Poisson's ratio	-	.25
Angle of internal friction	-	30 degrees
Cohesion	-	23.4 N/cm^2 (34 psi)
Low Density Backfill:		
Poisson's ratio	-	.20
Angle of internal friction	-	36 degrees
Cohesion	-	24.8 N/cm^2 (36.0 psi)

TABLE 8

ANALYTICAL APPROACH

MEASUREMENT	ANALYTICAL APPROACH					
	ROOF IDEALIZATION	SPRING/MASS IDEALIZATION	FOUNDATION IDEALIZATION	WALL IDEALIZATION	HANDBOOK	ESTIMATE
Accelerations						
113	X	X				
114	X	X				
115					X	
116		X			X	
117					X	
118		X			X	
119					X	
120		X				
121					X	
Free Field						
122 to 129					X	X
Velocities						
240		X				
241	X	X				
242	X	X				
243					X	
244		X	X			
245					X	
246			X			
247					X	
248		X			X	
249					X	
250		X			X	
251					X	

TABLE 8 (Continued)

MEASUREMENT	ANALYTICAL APPROACH					
	ROOF IDEALIZATION	SPRING/MASS IDEALIZATION	FOUNDATION IDEALIZATION	WALL IDEALIZATION	HANDBOOK	ESTIMATE
Free Field						
252 to 259					X	X
Blast Pressures						
047 to 051						X
052 to 053					X	
Interface Pressures						
554				X	X	
555				X	X	
556				X	X	
557		X	X			
558		X	X			
559		X	X			
560				X	X	
561				X	X	
562				X	X	
Strain						
517				X	X	
518				X	X	
519				X	X	
520				X	X	
521	X					
522	X					
523	X					
524	X					
525	X	X				
526					X	

TABLE 8 (Continued)

MEASUREMENT	ANALYTICAL APPROACH					
	ROOF IDEALIZATION	SPRING/MASS IDEALIZATION	FOUNDATION IDEALIZATION	WALL IDEALIZATION	HANDBOOK	ESTIMATE
Strain						
527	X	X				
528			X			
529			X			
530	X	X				
531	X	X				
532	X	X				
533	X	X				
534	X	X				
535	X	X				
536				X		
537				X		
538				X		
539				X		
540		X				
541				X		

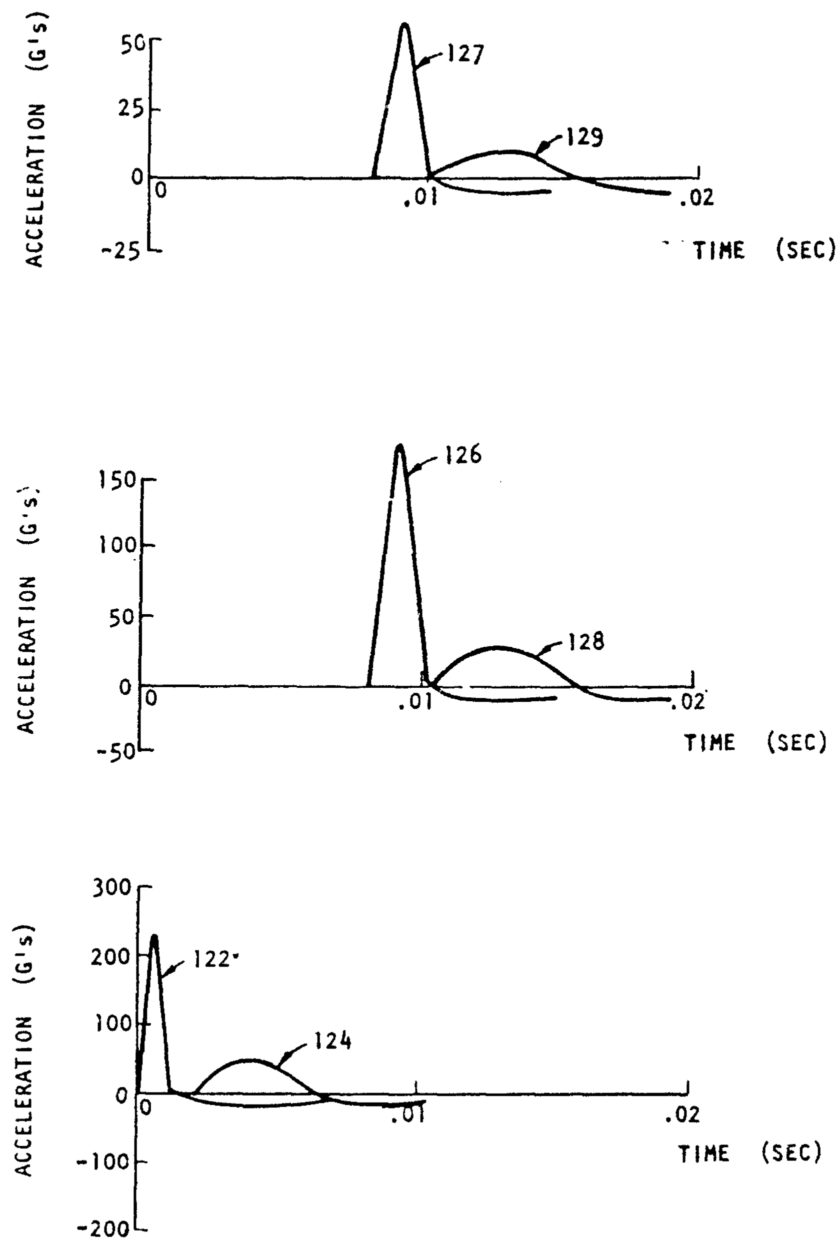


Figure 28. Predictions (Measurement No. 122, 124, 126, 127, 128, 129)

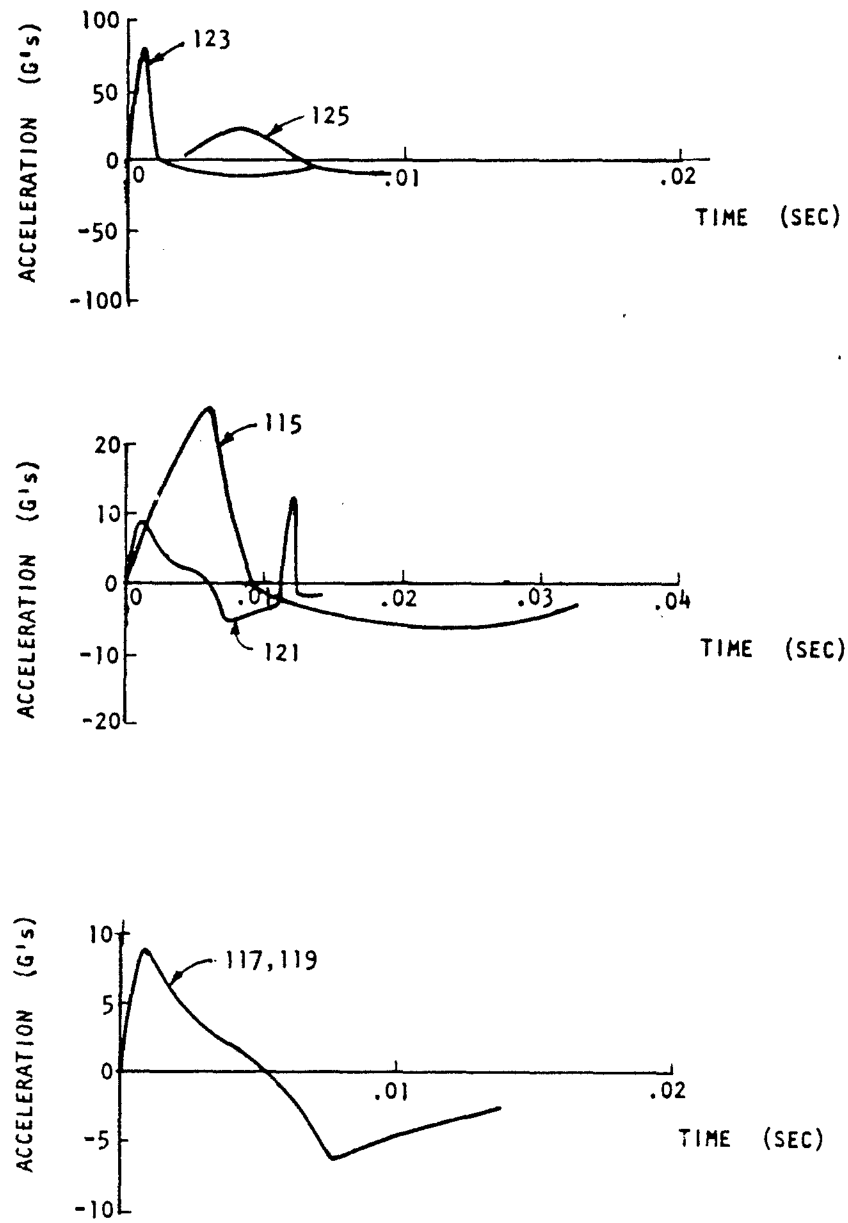


Figure 29. Predictions (Measurements No. 115, 117, 119, 121, 123, 125)

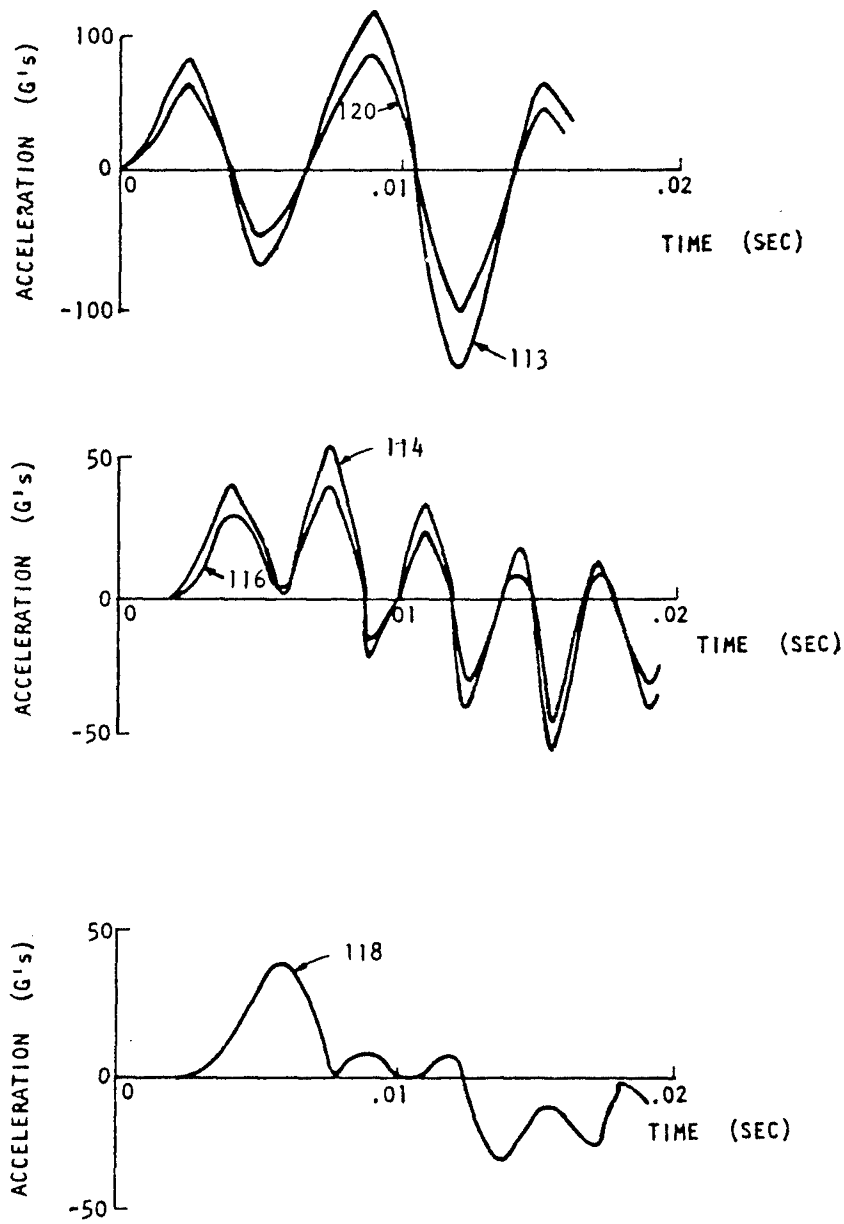


Figure 30. Predictions (Measurements No. 113, 114, 116, 118, 120)

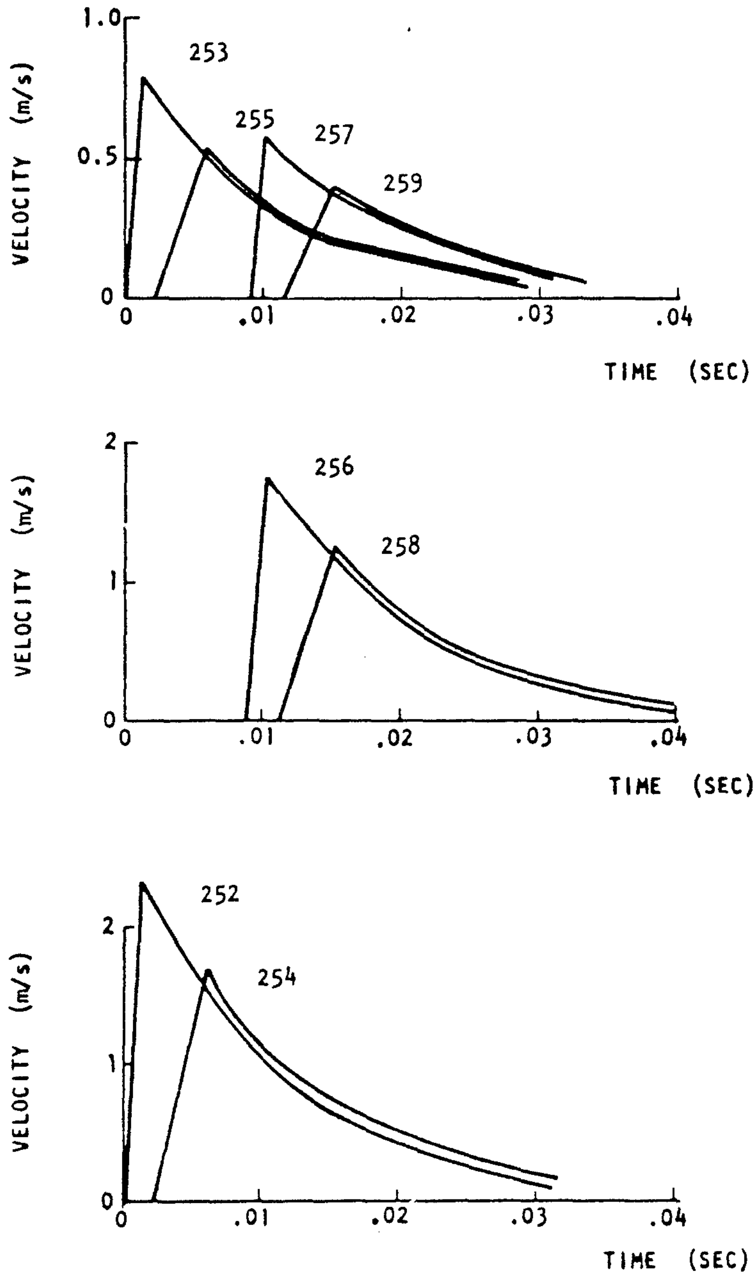


Figure 31. Predictions (Measurements No. 252, 253, 254, 255, 256, 257, 258, 259)

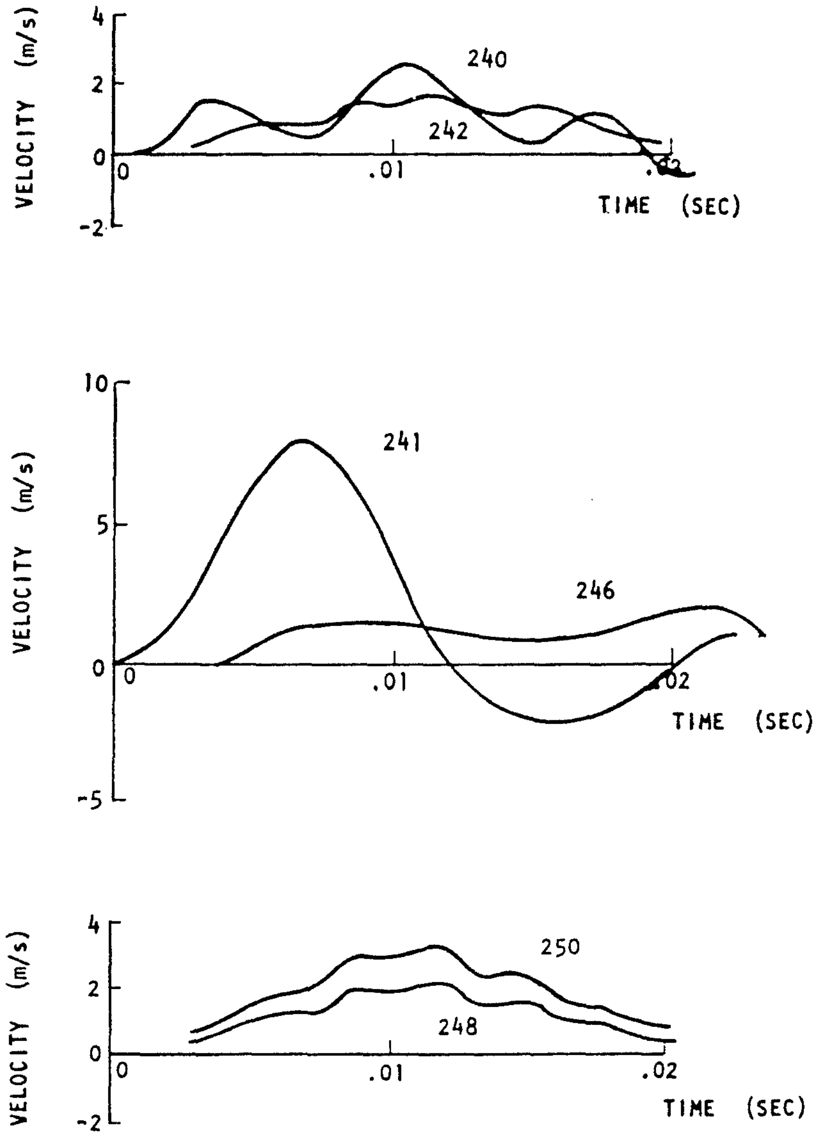


Figure 32. Predictions (Measurements No. 240, 241, 242, 248, 250)

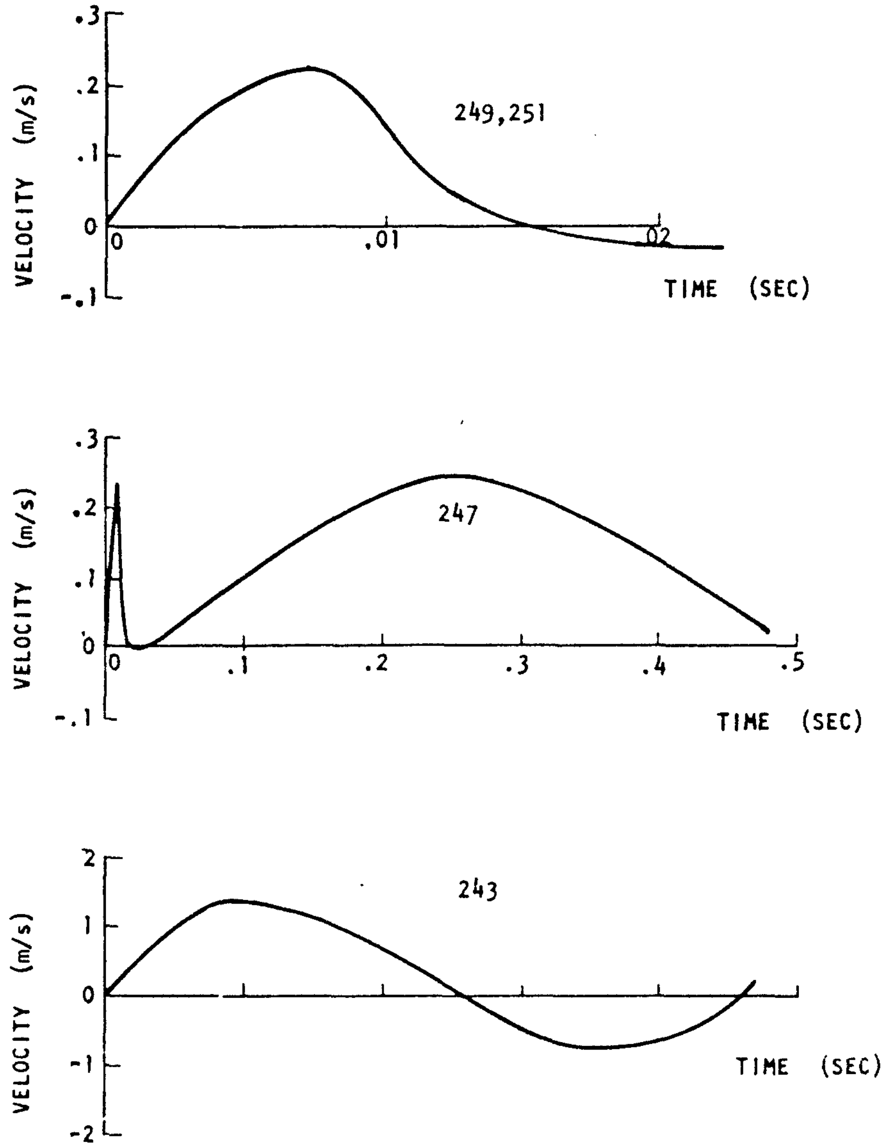


Figure 33. Predictions (Measurements No. 243, 247, 249, 251)

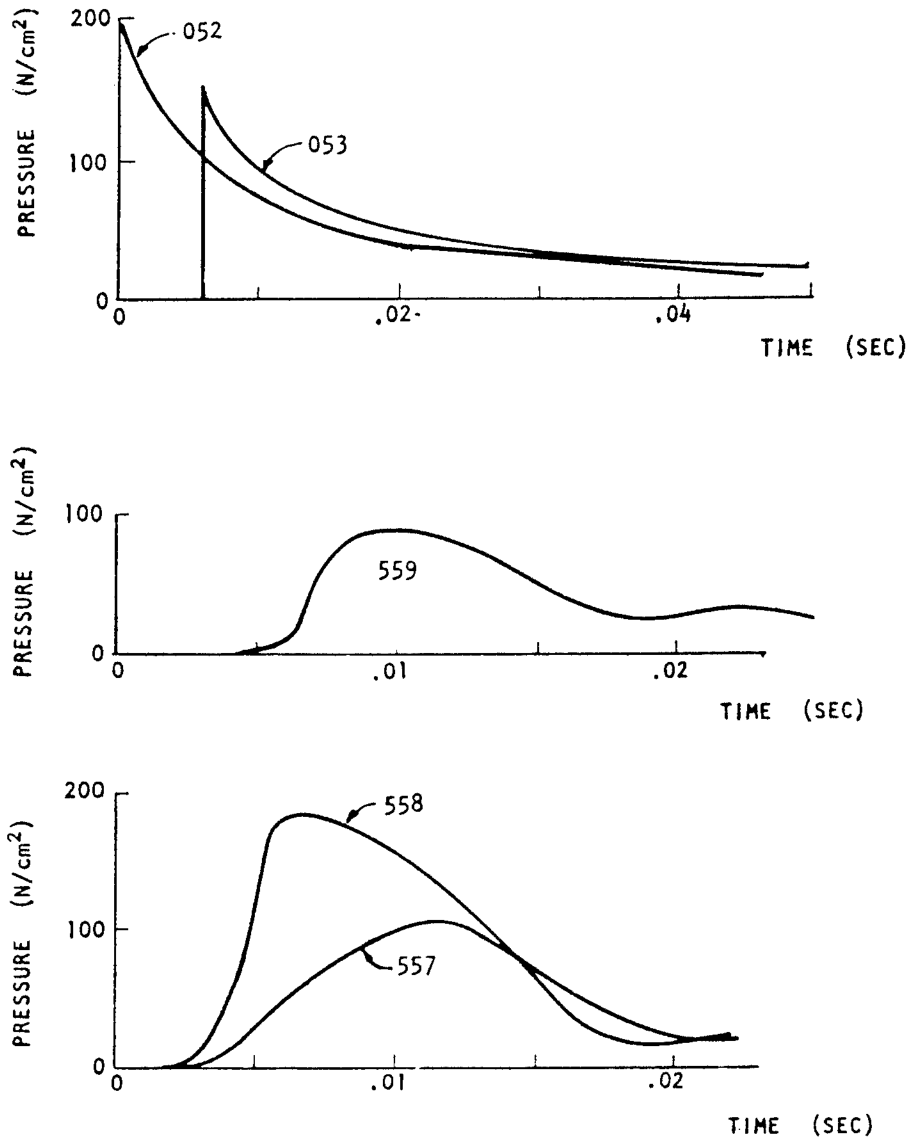


Figure 34. Predictions (Measurements No. 052, 053, 557, 558, 559)

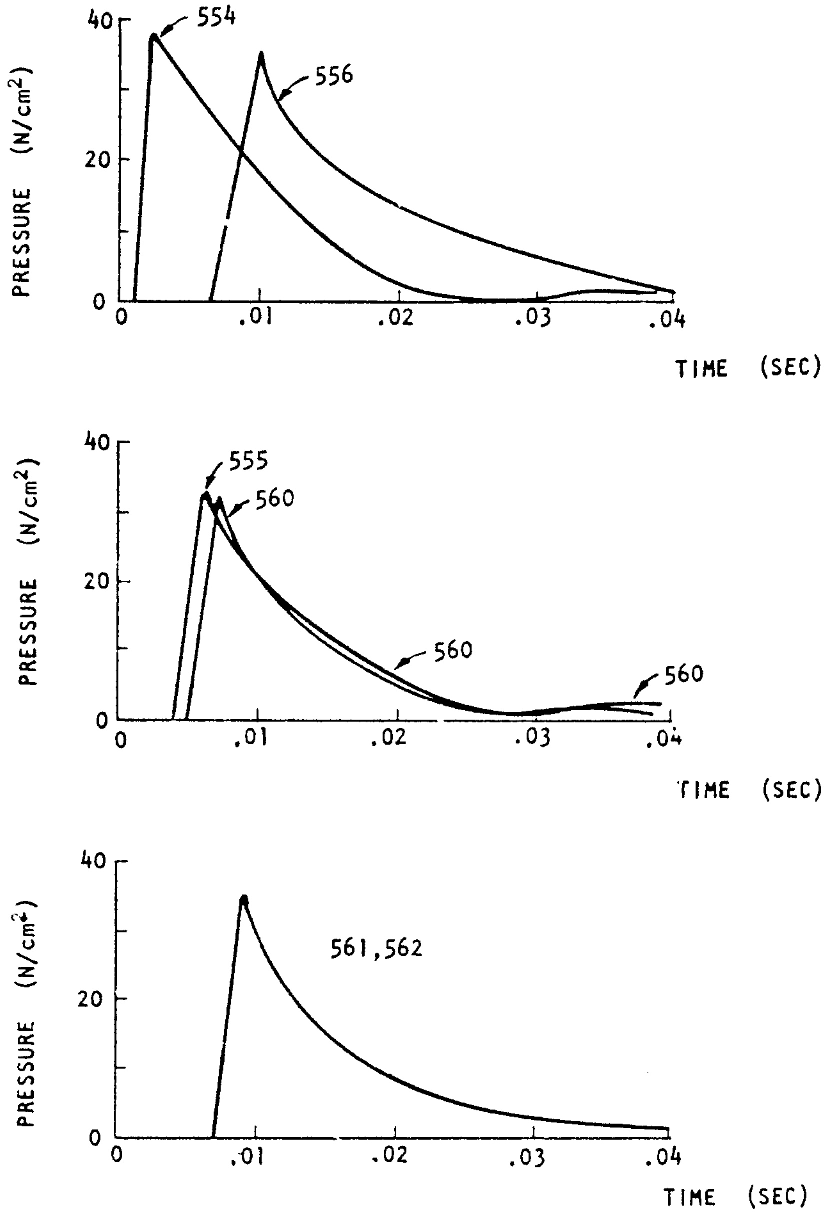


Figure 35. Predictions (Measurements No. 554, 555, 556, 560, 561, 562)

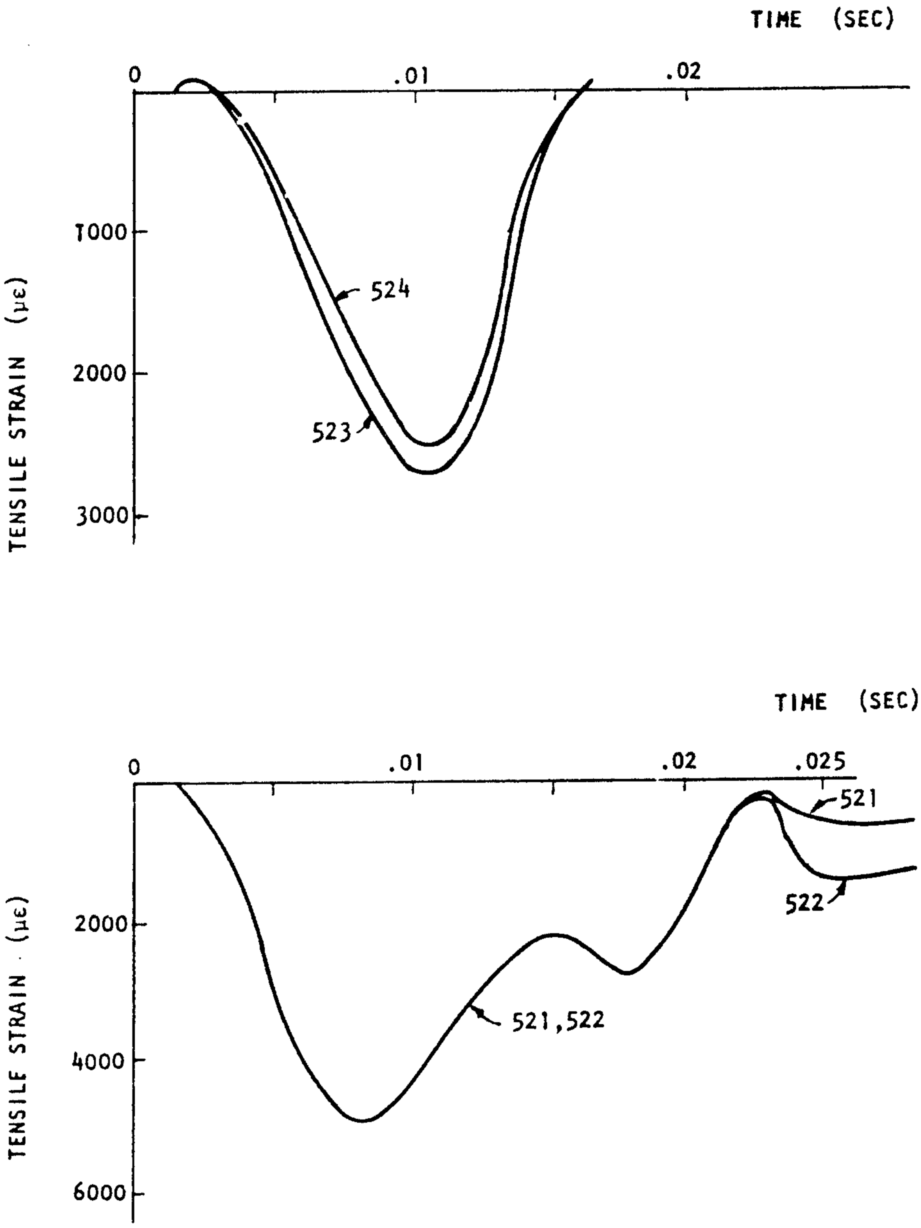


Figure 36. Predictions (Measurements No. 521, 522, 523, 524)

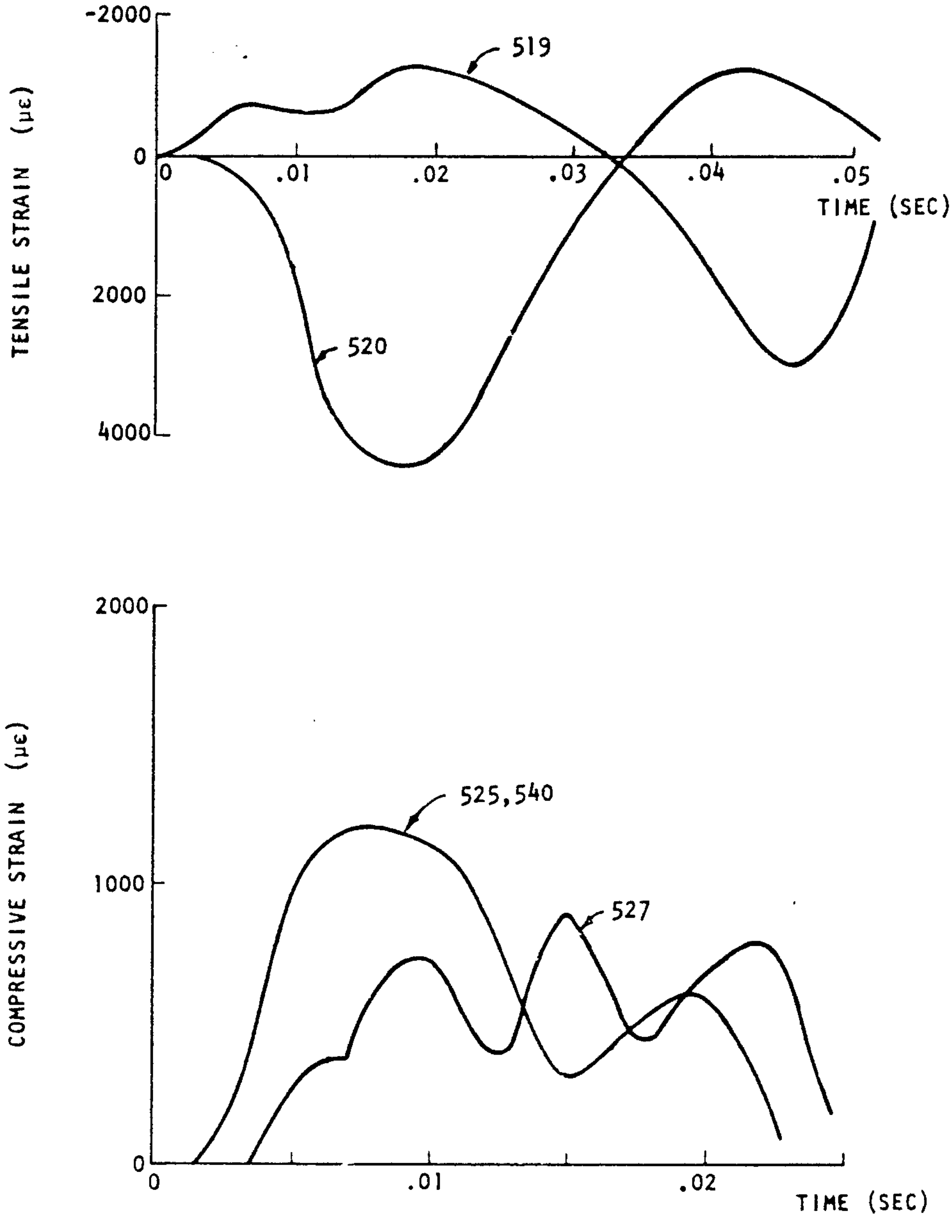
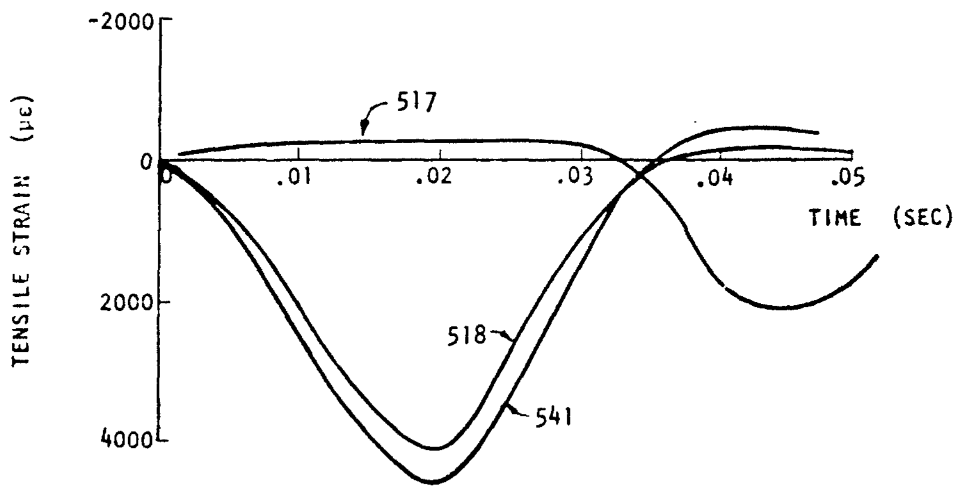


Figure 37. Predictions (Measurements No. 519, 520, 525, 527, 540)



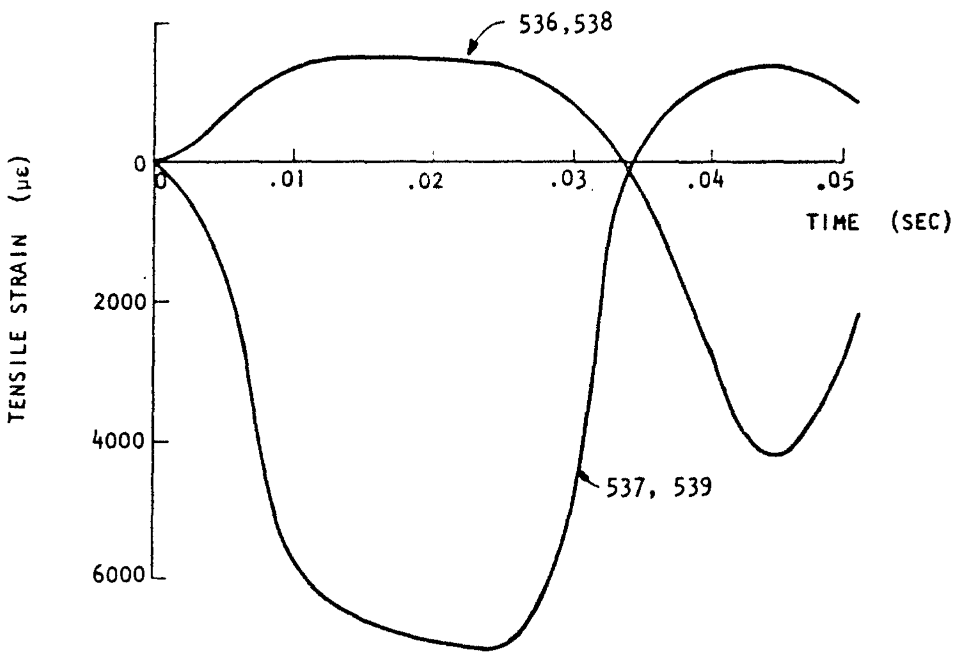


Figure 38. Predictions (Measurements No. 536, 537, 538, 539, 517, 518, 541)

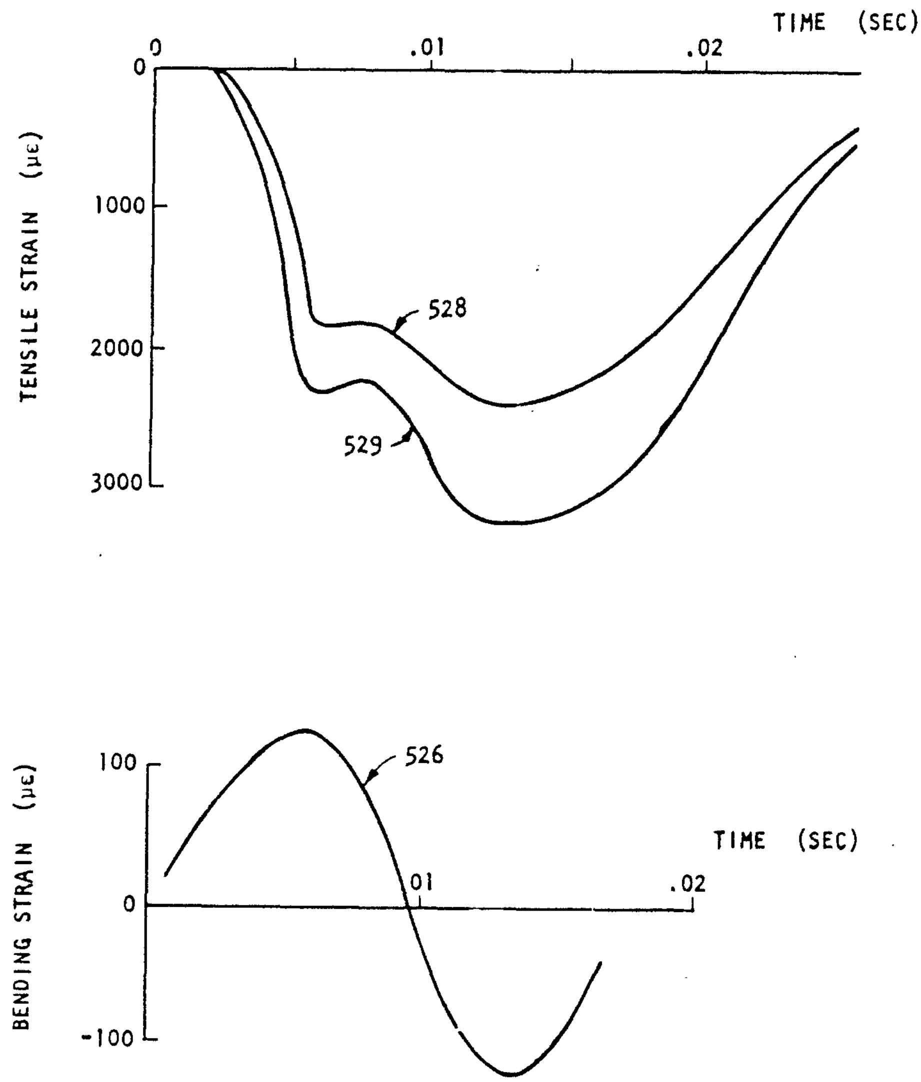


Figure 39. Predictions (Measurements No. 526, 528, 529)

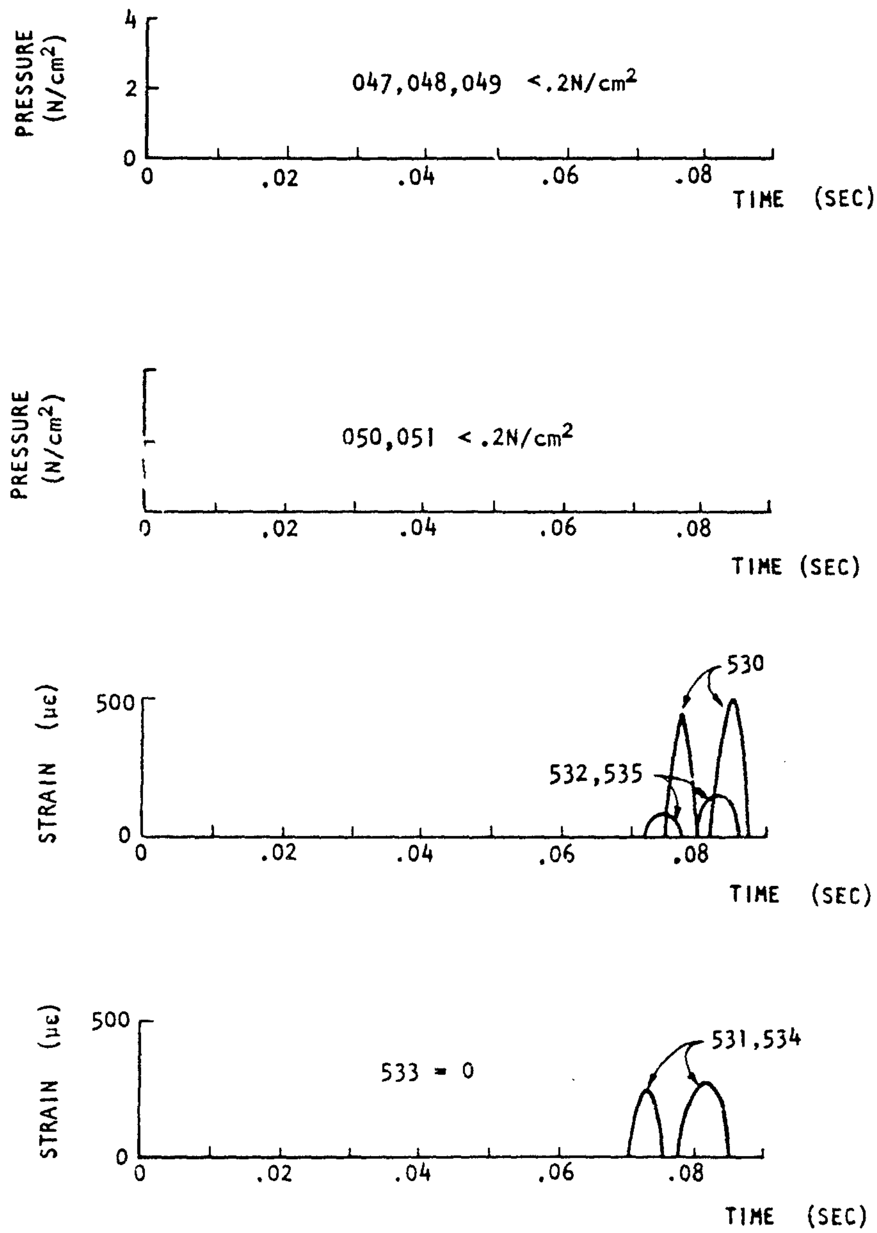


Figure 40. Predictions (Measurements No. 530, 531, 532, 533, 534, 535)

SECTION VII

TEST PLAN

1. PURPOSE

The purpose of the test is to determine the response of the Boeing aircraft shelter to a nuclear attack. This will be accomplished by measuring the loads, deflections, and motions of a 1/3 scale shelter model placed at the 250 psi range in the Dice Throw Event. The data that are gathered will be used to verify the analytical models used to design the shelter. The verification will be supported by a comparison of the test results with the predictions contained in Section VI of this report. The data will also be used as a basis for predicting the blast, shock, and vibration environments that the equipment and personnel inside the shelter must survive.

2. MEASUREMENTS (Figure 41)

a. Strain Gages

Strain gages are placed on important structural elements to indicate the load patterns in the structure. They are generally placed at points where the largest strains are expected and at points where excessive strains would cause catastrophic failure. Table 9 summarizes the strain gage location and designation.

The following strain gages are installed on the reinforcing steel in the shelter structure. Gages 517 and 518 are on the inner and outer horizontal re-bar at the top of the northeast wall and 519 and 529 are on the vertical bars at the bottom of the wall. These gages are included to indicate the strain at the points where large moments are expected. They will be used with the gages that measure soil forces on the wall to determine the stress distribution in the wall. Gage 541, on the inner horizontal re-bars at the top of the north wall, is included to indicate the strain patterns in the north wall. Gages 536, 537, 538, and 539 measure strain in the inner and outer horizontal reinforcing bars near the top of the corners where the north, northeast and east walls join. Gages 521 and 522 are attached to the upper re-bar in the ceiling above the northwest column.

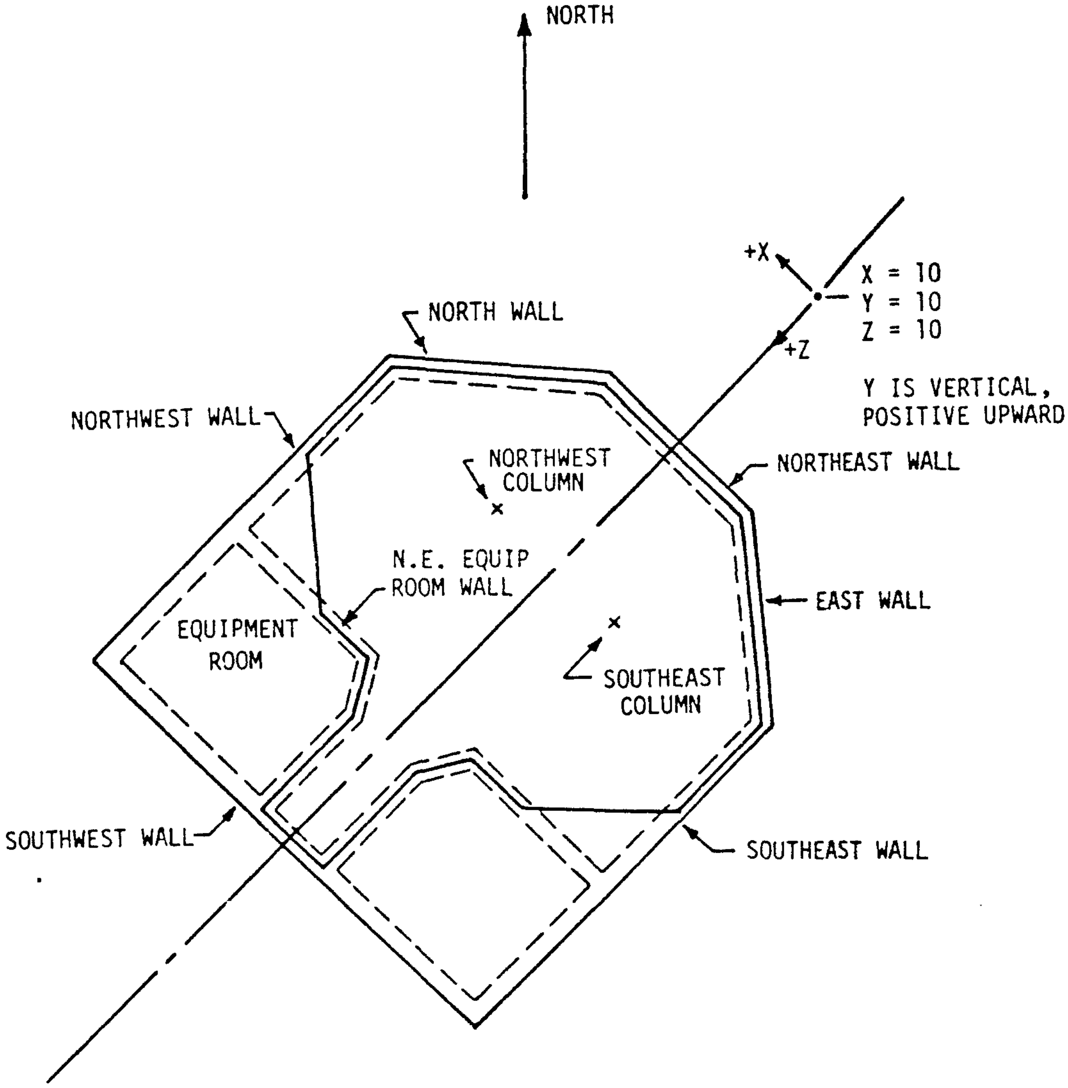


Figure 41. Aircraft Shelter Nomenclature

TABLE 9 MEASUREMENT DESIGNATIONS - STRAIN GAGES

GAGE NO.	MEAS. NO.	MEASUREMENT DESIGNATION	DESCRIPTION	LOCATION
SE1	517	B-SD-10.00-9.16-13.02-SE-HT	1	Top of NE Wall
SE2	518	B-SD-10.00-9.16-13.23-SE-HT	1	Top of NE Wall
SE3	519	B-SD-10.00-7.48-13.23-SE-V	1	Bottom of NE Wall
SE4	520	B-SD-10.00-7.48-13.02-SE-V	1	Bottom of NE Wall
SE5	521	B-SD-11.27-9.98-15.69-SE-HL	1	Roof Above Northwest Column
SE6	522	B-SD-11.27-9.98-15.69-SE-HT	1	Roof Above Northwest Column
SE7	523	B-SD-10.00-9.63-17.02-SE-HL	2	Middle of Roof
SE8	524	B-SD-10.00-9.63-17.02-SE-HT	2	Middle of Roof
SE9	525	B-SD-11.27-9.26-15.70-SE-V	3	Top of Northwest Column
SE10	526	B-SD-11.27-7.94-15.70-SE-V	4	Bottom of Northwest Column
SE11	527	B-SD-11.41-9.24-18.64-SE-V	6	NE Wall Equip. Room (Upper Level)
SE12	528	B-SD-10.00-7.38-16.86-SE-HL	1	Middle of Foundation
SE13	529	B-SD-10.00-7.38-16.86-SE-HT	1	Middle of Foundation
SE14	530	B-SD-11.35-9.22-18.43-SE-V	5	Roof Tie Down - NE Equip. Room Wall
SE15	531	B-SD-10.00-9.22-13.35-SE-V	5	Roof Tie Down - NE Wall
SE16	532	B-SD-13.71-9.22-15.42-SE-V	5	Roof Tie Down - NW Wall
SE17	533	B-SD-10.00-9.22-21.29-SE-V	5	Roof Tie Down - SW Wall
SE18	534	B-SD-11.22-9.22-13.35-SE-V	5	Roof Tie Down - NE Wall
SE19	535	B-SD-6.29-9.22-15.42-SE-V	5	Roof Tie Down - SE Wall

TABLE 9 MEASUREMENT DESIGNATIONS - STRAIN GAGES (CONTINUED)

GAGE NO.	MEAS. NO.	MEASUREMENT DESIGNATION	DESCRIPTION	LOCATION
SE20	536	B-SD-11.59-9.16-13.24-SE-HT	1	Top of NE Wall (North Corner)
SE21	537	B-SD-11.65-9.16-13.17-SE-HT	1	Top of NE Wall (North Corner)
SE22	538	B-SD-8.41-9.16-13.24-SE-HT	1	Top of NE Wall (East Corner)
SE23	539	B-SD-8.35-9.16-13.17-SE-HT	1	Top of NE Wall (East Corner)
SE24	540	B-SD-8.73-9.26-15.70-SE-V	3	Top of Southeast Column
SE25	541	B-SD-12.61-9.24-14.19-SE-HT	1	Top of North Wall

1 Axial strain in reinforcing bar.

2 Axial strain in roof bottom plate.

3 2 gages centered on opposite flanges averaged to measure axial strain.

4 2 gages on opposite sides of a flange differenced to measure differential strain.

5 Gage on either side of round bar averaged to measure axial strain.

6 Gages on 2 reinforcing bars averaged to measure average axial strain.

NOTE: See Sheet 14 for built in instrumentation and lead wire tube installation.

They are intended to measure the strain in both horizontal axes caused by the flexure of the roof over the column. Gages 528 and 529 are attached to the upper re-bar in the foundation at the point where the maximum vertical displacement relative to the walls is expected. Gage 527 may be either embedded in the concrete of the northeast equipment room wall or attached to the vertical re-bar in the wall. In either configuration, the gage will measure the compressive strain in the wall. The gage is near the point where maximum wall compression is expected.

Strain gages 523 and 524 are installed to measure the horizontal strains in the steel bottom plate of the moveable roof. These gages are mounted at the point where maximum roof deflection will occur. Strain gages 525 and 540 are installed at the upper end of the columns and are configured to measure the axial strain in the columns. Gage 526 is installed in the lower end of the northwest column and is wired to measure the difference in strain between two flanges of the column. The differential strains will be used to calculate the bending moment in the column.

The strain gages on the roof tie-downs, 530 to 535 will measure the tensile strain in the tie bars if the roof tends to separate from the shelter. The tie-downs will be installed so they have a tensile strain of approximately 20 $\mu\varepsilon$. This will be accomplished by tightening the adjusting sleeve of one tie-down until it has strained 20 $\mu\varepsilon$ and noting the torque required. That torque will be applied to all other tie-downs and the data recording system will be set up to show zero strain in all tie-downs.

b. Accelerometers and Velocity Gages

Table 10 lists the accelerometers and Table 11 lists the velocity gages that are located in the aircraft shelter and in the adjacent soil. The velocity gages and accelerometers are provided to measure the shock environment at locations where equipment would be located in the full scale aircraft shelter. The data will also be compared with the predictions to verify the method of analyzing the aircraft shelter.

Accelerometer 113 and velocity gage 240 measure the vertical motions at the northeast end of the roof. Accelerometers 114 and 115 and velocity gages 242 and 243 measure the vertical and horizontal acceleration on the top of the northeast wall. The data from these gages will be used to

TABLE 10 MEASUREMENT DESIGNATIONS - ACCELEROMETERS

GAGE NO.	MEAS. NO.	MEASUREMENT DESIGNATION	LOCATION
A1	113	B-SD-10.00-9.63-13.45-A-V	NE End of Roof
A2	114	B-SD-10.00-9.43-13.25-A-V	Top of NE Wall
A3	115	B-SD-10.00-9.43-13.25-A-HL	Top of NE Wall
[illegible]	116	B-SD-11.65-9.10-18.73-A-V	NE Wall Equip. Room (Upper Level)
A5	117	B-SD-11.65-9.10-18.73-A-HL	NE Wall Equip. Room (Upper Level)
A6	118	B-SD-12.30-8.63-19.95-A-V	Equip. Room Floor (Upper Level)
A7	119	B-SD-12.30-8.63-19.95-A-HL	Equip. Room Floor (Upper Level)
A8	120	B-SD-13.65-9.63-15.70-A-V	Northeast Actuator - Upper Attach Pt.
A9	121	B-SD-13.65-9.63-15.70-A-HL	Northeast Actuator - Upper Attach Pt.
A10	122	B-SD-10.00-9.70-10.00-A-V	Free Field, .3 m Depth
A11	123	B-SD-10.00-9.70-10.00-A-HL	Free Field, .3 m Depth
A12	124	B-SD-10.00-7.60-10.00-A-V	Free Field, 2.4 m Depth
A13	125	B-SD-10.00-7.60-10.00-A-HL	Free Field, 2.4 m Depth
A14	126	B-SD-10.00-9.70-24.59-A-V	Free Field, .3 m Depth
A15	127	B-SD-10.00-9.70-24.59-A-HL	Free Field, .3 m Depth
A16	128	B-SD-10.00-7.60-24.59-A-V	Free Field, 2.4 m Depth
A17	129	B-SD-10.00-7.60-24.59-A-HL	Free Field, 2.4 m Depth

TABLE 11 MEASUREMENT DESIGNATIONS - VELOCITY GAGES

GAGE NO.	MEAS. NO.	MEASUREMENT DESIGNATION	LOCATION
V1	240	B-SD-10.00-9.63-13.45-V-V	NE End of Roof
V2	241	B-SD-10.00-9.63-17.02-V-V	Middle of Roof
V3	242	B-SD-10.00-9.43-13.25-V-V	Top of NE Wall
V4	243	B-SD-10.00-9.43-13.25-V-HL	Top of NE Wall
V7	246	B-SD-10.00-7.39-16.86-V-V	Middle of Foundation
V8	247	B-SD-10.00-7.39-16 86-V-HL	Middle of Foundation
V9	248	B-SD-11.65-9.10-18.73-V-V	NE Wall Equip. Room (Upper Level)
V10	249	B-SD-11.65-9.10-18.73-V-HL	NE Wall Equip. Room (Upper Level)
V11	250	B-SD-12.30-8.63-19.95-V-V	Equip. Room Floor (Upper Level)
V12	251	B-SD-12.30-8.63-19.95-V-HL	Equip. Room Floor (Upper Level)
V13	252	B-SD-10.00-9.70-10.00-V-V	Free Field, .3 m Depth
V14	253	B-SD-10.00-9.70-10.00-V-HL	Free Field, .3 m Depth
V15	254	B-SD-10.00-7.60-10.00-V-V	Free Field, 2.4 m Depth
V16	255	B-SD-10.00-7.60-10.00-V-HL	Free Field, 2.4 m Depth
V17	256	B-SD-10.00-9.70-24.59-V-V	Free Field, .3 m Depth
V18	257	B-SD-10.00-9.70-24.59-V-HL	Free Field, .3 m Depth
V19	258	B-SD-10.00-7.60-24.59-V-V	Free Field, 2.4 m Depth
V20	259	B-SD-10.00-7.60-24.59-V-HL	Free Field, 2.4 m Depth

predict the shock loads on the roof tie-down attachment hardware.

Accelerometers 116 and 117 and velocity gages 248 and 249 are located near the top of the northeast wall of the equipment room to measure vertical and horizontal accelerations. Accelerometers 118 and 119 and velocity gages 250 and 251 are on the equipment room floor. The data from these gages will be used to predict the shock environment on items mounted in the equipment room. The equipment room velocity gages should provide a good indication of the gross motions of the shelter structure.

Accelerometers 120 and 121 measure vertical and horizontal acceleration of the roof at the point where the northeast actuator is attached. The data will be used to predict the shock loads on the upper actuator attachment and the roof tie-down attachments.

Velocity gage 241 measures vertical velocity of the roof at the point where maximum motion is predicted. The data from gage 241 will be compared with roof dynamic analysis predictions to verify the analysis methods.

Velocity gages 246 and 247 measure vertical and horizontal velocity of the foundation at the point where maximum motion is predicted. The data from the velocity gages will be compared with the foundation motion predictions to determine the accuracy of foundation analyses.

Accelerometers 122 to 129 and velocity gages 252 to 259 are located in the soil 3 meters northeast of the northeast wall and 3 meters southwest of the southwest wall. These gages are provided to measure free field motion near the aircraft shelter. The data will be used with the structural measurements to determine the effect of the free field motions on the structural response.

c. Pressure Measurements (Table 12)

The air pressure gages, 047 to 051, are provided to measure the pressure rise in the shelter caused by the motion of the roof and leakage past the seals. The gages are placed where leakage would either be most likely to occur or where it would damage the aircraft. The five gages are required because the leakage pressure is expected to be rapidly attenuated with distance so it may be difficult to detect and locate leakage sources with a smaller number of gages.

TABLE 12 MEASUREMENT DESIGNATION - PRESSURE GAGES

GAGE NO.	MEAS. NO.	MEASUREMENT DESIGNATION	LOCATION
BP1	047	B-SD-10.97-9.43-18.71-BP-HL	Seal Leakage Pressure, Top of Equipment Room Wall
BP2	048	B-SD-13.81-9.43-16.87-BP-HT	Seal Leakage Pressure, Top of NW Wall
BP3	049	B-SD-9.72-9.43-13.25-BP-HL	Seal Leakage Pressure, Top of NE Wall
BP4	050	B-SD-10.55-9.43-21.19-BP-HT	Seal Leakage Pressure, Top of SW Wall
BP5	051	B-SD-10.51-7.59-16.51-BP-V	Seal Leakage Pressure, Center of Elevator Floor
BP6	052	B-SD-10.86-10.00-14.09-BP-V	Surface Overpressure, NE end of Shelter
BP7	053	B-SD-10.86-10.00-21.28-BP-V	Surface Overpressure, SW end of Shelter
IP1	554	B-SD-10.00-9.39-13.00-IP-HL	Top of NE Wall (Outside Wall)
IP2	555	B-SD-10.00-8.48-13.00-IP-HL	Center of NE Wall (Outside Wall)
IP3	556	B-SD-10.00-7.26-13.00-IP-HL	Bottom of NE Wall (Outside Wall)
IP4	557	B-SD-10.00-6.88-13.46-IP-V	Under NE Wall
IP5	558	B-SD-11.27-6.88-15.70-IP-V	Under North Column Footings
IP6	559	B-SD-10.00-6.88-16.86-IP-V	Under Center of Building
IP7	560	B-SD-12.77-8.48-14.09-IP-HL	Center of North Wall (Outside Wall)
IP8	561	B-SD-14.06-8.48-15.97-IP-HT	Center of NW Wall (Outside Wall)
IP9	562	B-SD-5.94-8.48-15.97-IP-HT	Center of SE Wall (Outside Wall)

Pressure gages 052 and 053 measure the air blast overpressure at each end of the shelter. The data will be compared with the predicted overpressure pulse used in the shelter analysis to assess the effect of any differences between the predicted and actual pressures.

d. Soil Properties

The design of the 1/3 scale aircraft shelter and the prediction of its response are based on soil properties measured in the area of the German structures at the Dice Throw site. A visual comparison must be made between the soil at the hard flush aircraft shelter site and the soil at the German structures site so any soil differences can be accounted for in the comparison between test results and test predictions. The in-situ density of the backfill placed around the shelter must also be determined so its effect on the structural response can be evaluated.

e. Concrete Properties

Standard cylindrical test specimens of the concrete used in the fixed roof, moveable roof, foundation and northeast wall will be taken as the shelter is poured. These test specimens shall be loaded to failure in an unconfined compression test on the day of the test. A stress versus strain from zero load to failure will be required for each specimen.

f. Motion Picture Cameras

Motion picture cameras are required to film the interfaces between the northwest column and the moveable roof and between the northeast equipment room wall and the moveable roof. The cameras are required to measure the vertical separation between the column and the roof and to measure the horizontal motion of the roof relative to the equipment room wall and the column. A camera speed of 1000 frames/second is required to adequately measure the motion.

g. Scratch Gages

A scratch gage is required at the northwest column to measure relative motion between the column and the roof. This gage should be able to accommodate upward roof movement of 3 inches, downward 1/2 inch, and 1 inch in all horizontal directions. It shall record vertical and longitudinal motion (motion toward and away from Ground Zero). The scratch gage shall

be in the field of view of the motion picture cameras so a displacement history can be determined from the combined data.

h. Survey Requirements

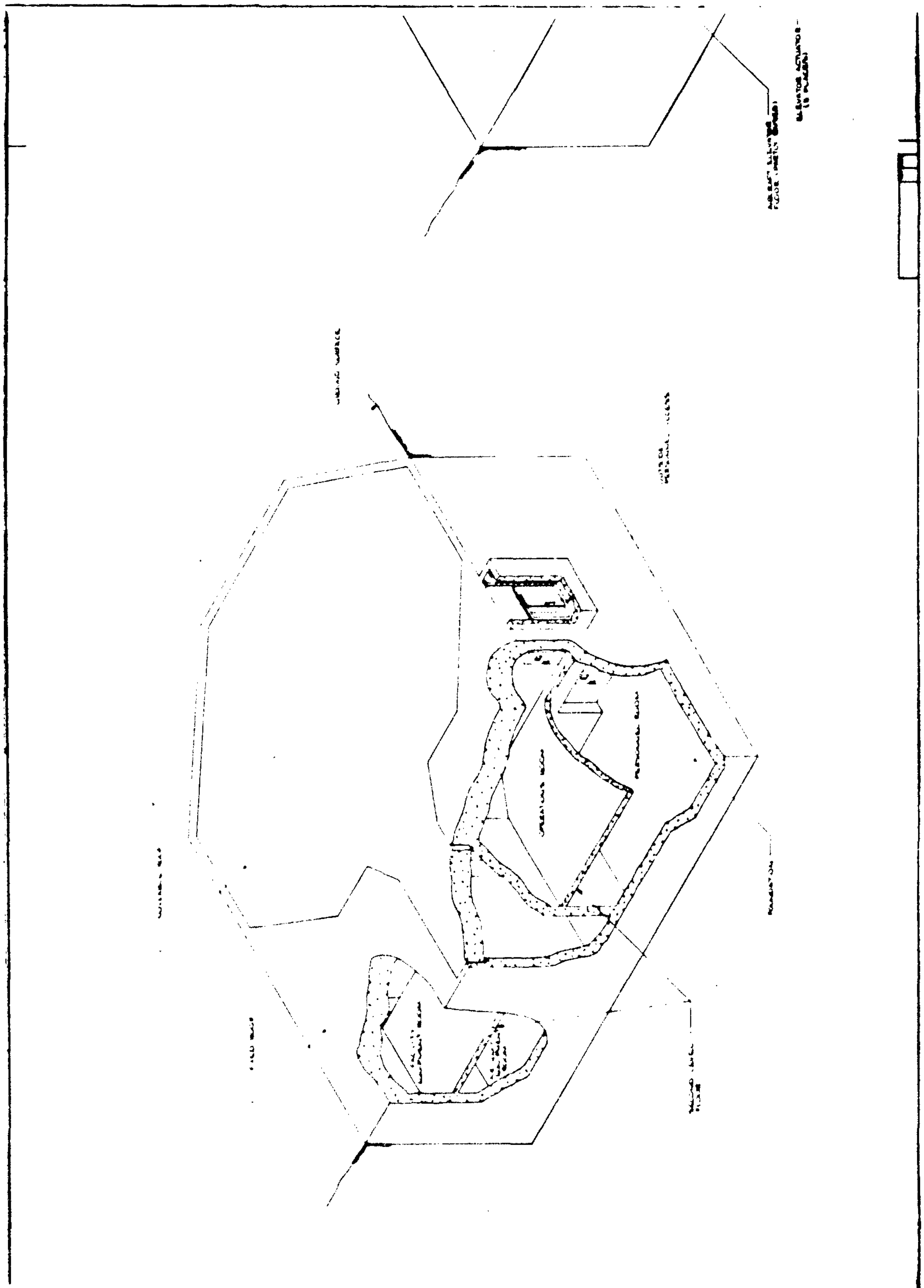
A post test survey is required to determine the permanent displacement of the shelter and the adjacent soil. This survey shall use the bench marks established for the initial survey of the structure. Expected vertical and horizontal permanent displacements are between zero and 2 inches.

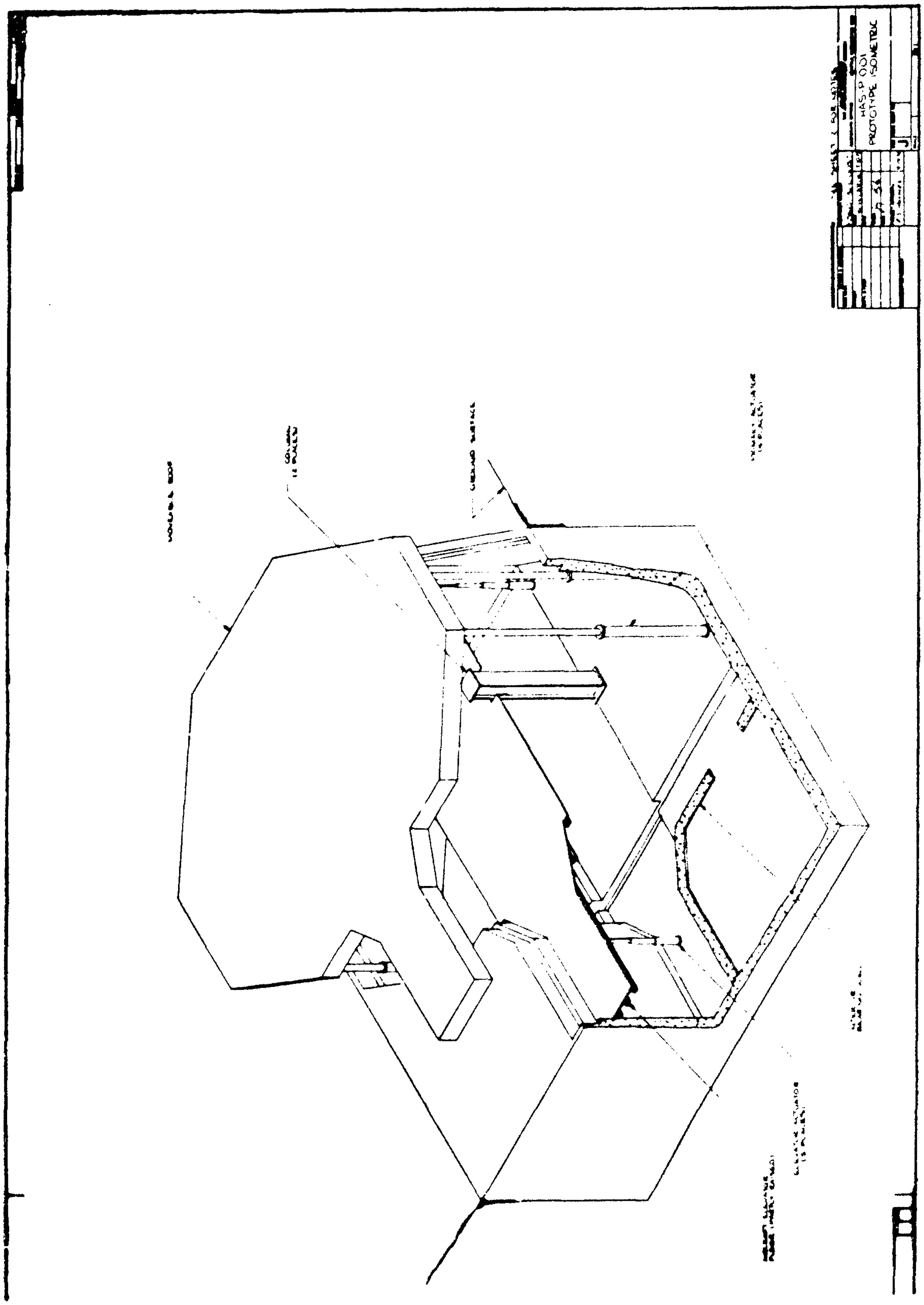
3. DATA REDUCTION

Data from the active gages specified in Tables 9, 10, 11, and 12 shall be recorded on magnetic tape. Initial results should be plots of the unfiltered data in gage units (micro-strain, m/sec, g's, N/m^2). Most of the data will be usable in that form. The data analyst will have to specify any filtering or other data preparation as a result of examining the unfiltered data. Shock spectra should be computed for all accelerometers and velocity gages.

APPENDIX A

PROTOTYPE DRAWINGS

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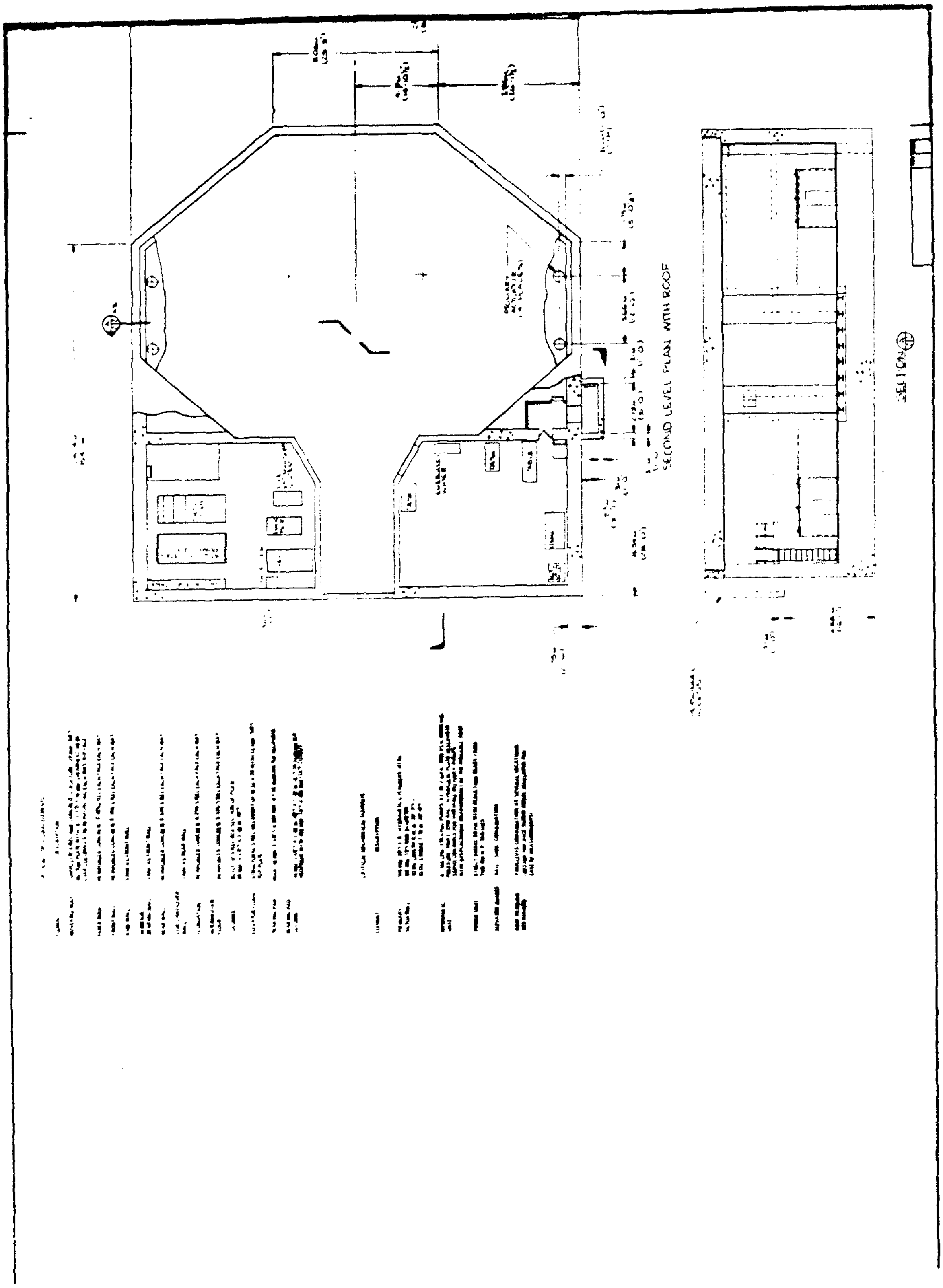
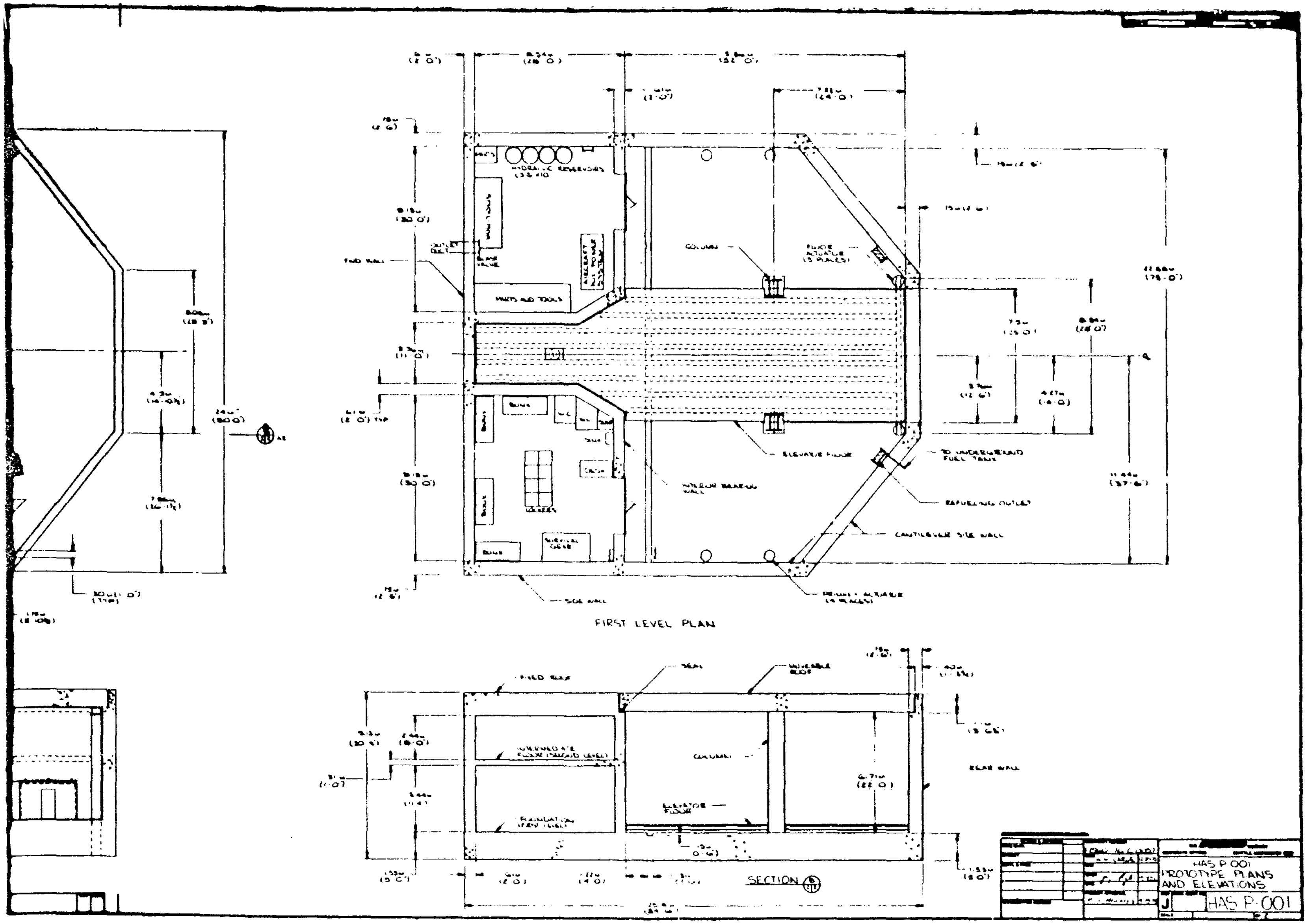

SECOND LEVEL PLAN WITH ROOF
SECTION A


FIRST LEVEL PLAN
SECTION
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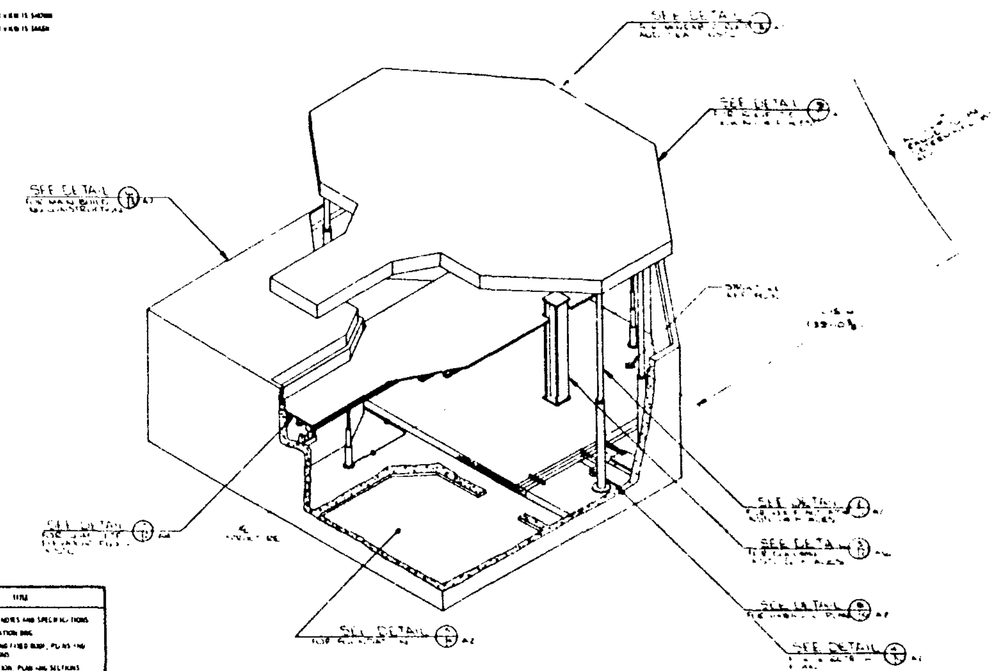
PROTOTYPE PLANS
AND ELEVATIONS
HAS P 001
HYDRAULIC RESERVOIRS
PARTS AND TOOLS
COLUMN
ELEVATOR FLOOR
INTERIOR BEARING WALL
TO UNDERGROUND FUEL TANK
REFUELING OUTLET
CANTILEVER SIDE WALL
SIDE WALL
END WALL
REAR WALL
COLUMN
ELEVATOR FLOOR

APPENDIX B

MODEL DRAWINGS



DRAWING INDEX

SHEET	SHEET CODE NO	TITLE
1	G-1	GENERAL NOTES AND SPECIFICATIONS
2	S-1	INSTALLATION DWG
3	S-2	WALLS AND FIXED ROOF, PLANS AND ELEVATIONS
4	S-3	FOUNDATION, PLAN AND SECTIONS
5	S-4	MOVEABLE ROOF
6	S-5	ROOF INSTALLATION AND SEAL DETAILS
7	S-6	DETAILS
8	S-7	ELEVATOR FLOOR
9	S-8	MISC. DETAILS AND SECTIONS
10	P-1	PIPING PLAN
11	P-2	HYDRAULIC SCHEMATIC AND DETAILS
12	E-1	PLAN AND CONTROL SCHEMATIC
13	E-2	DETAILS
14	[illegible]	BUILT IN INSTRUMENTATION LOCATIONS

SUPPLIER INDEX

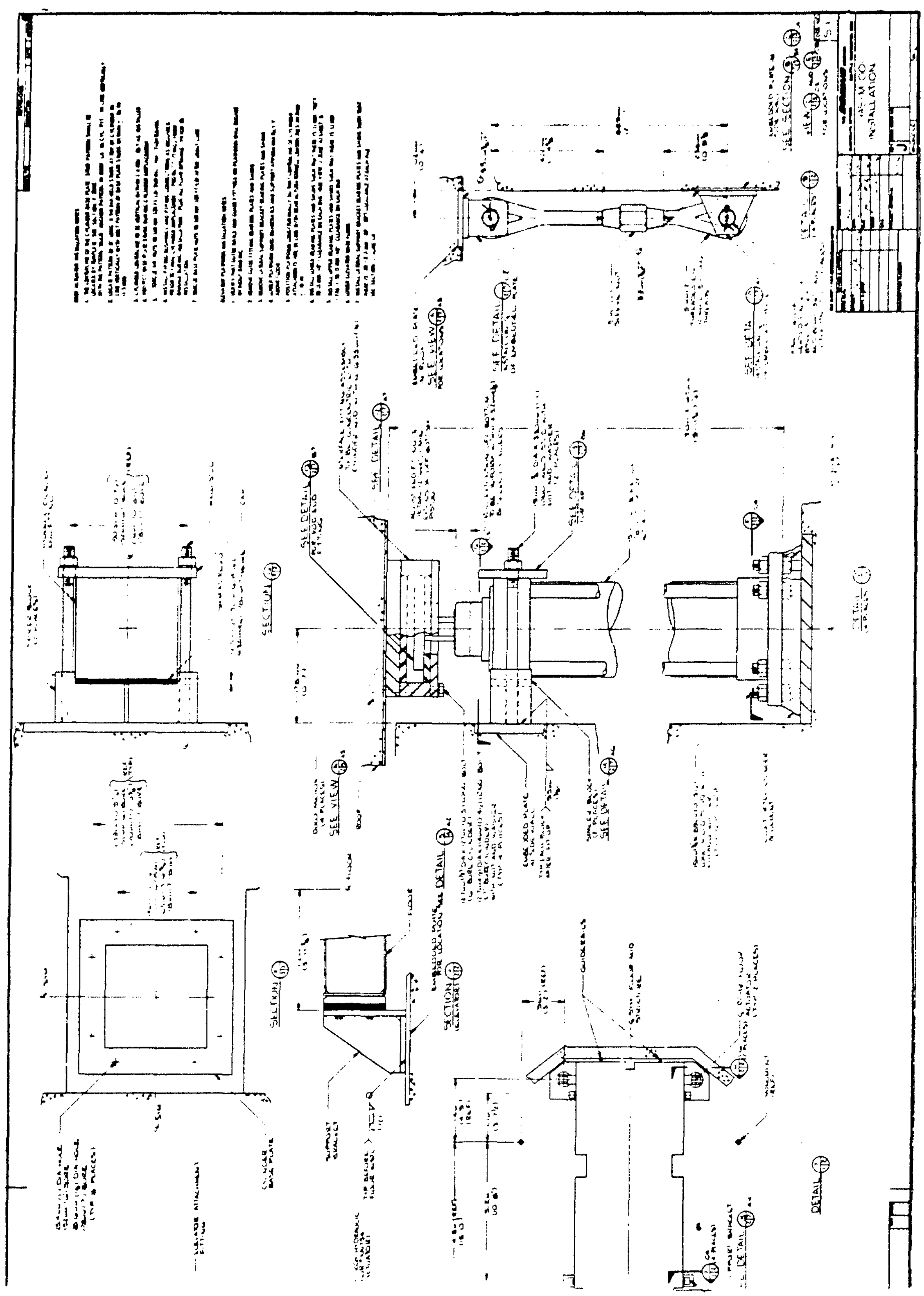
SYSTEM SUPPLIER

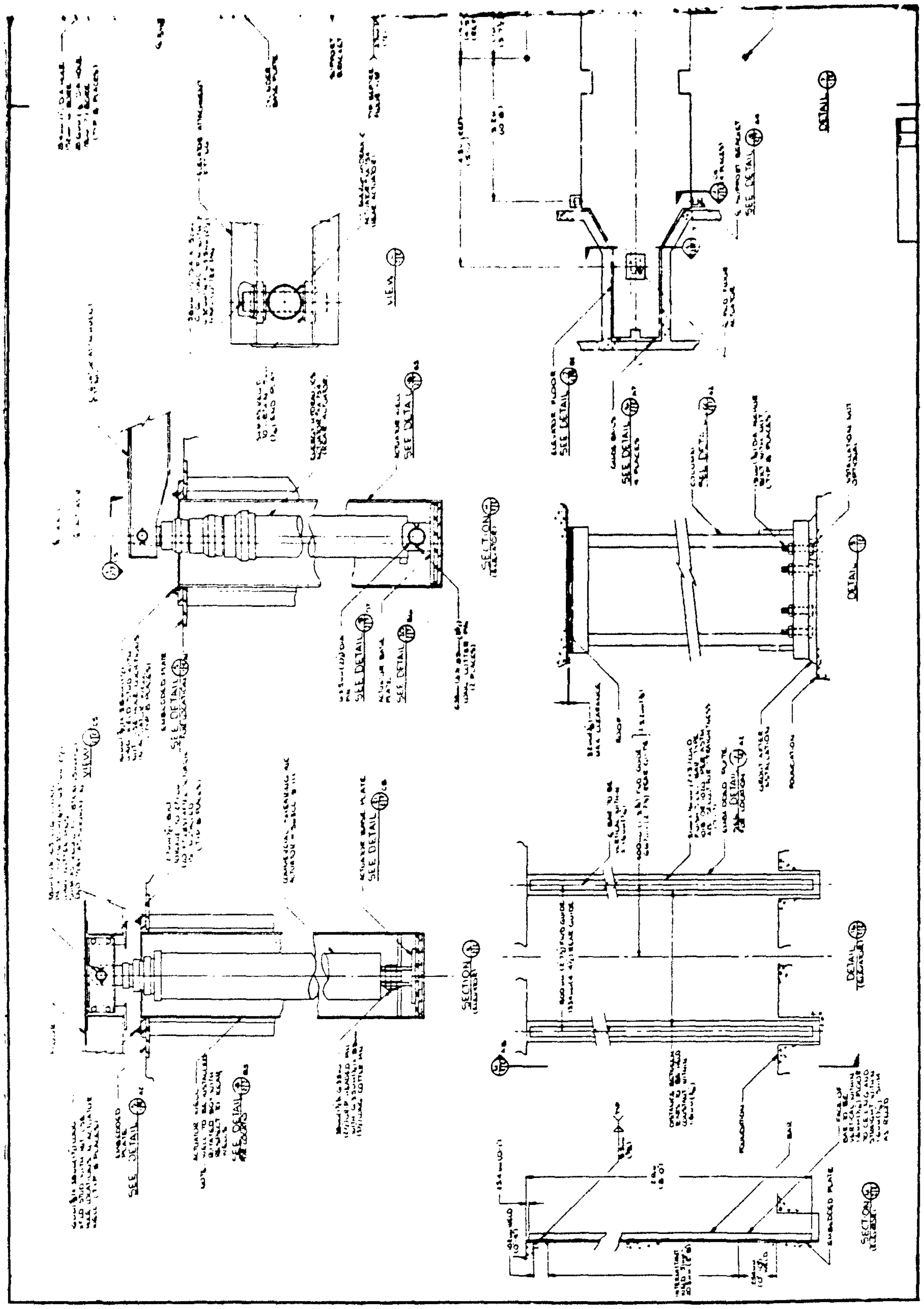
COMPONENT SUPPLIERS

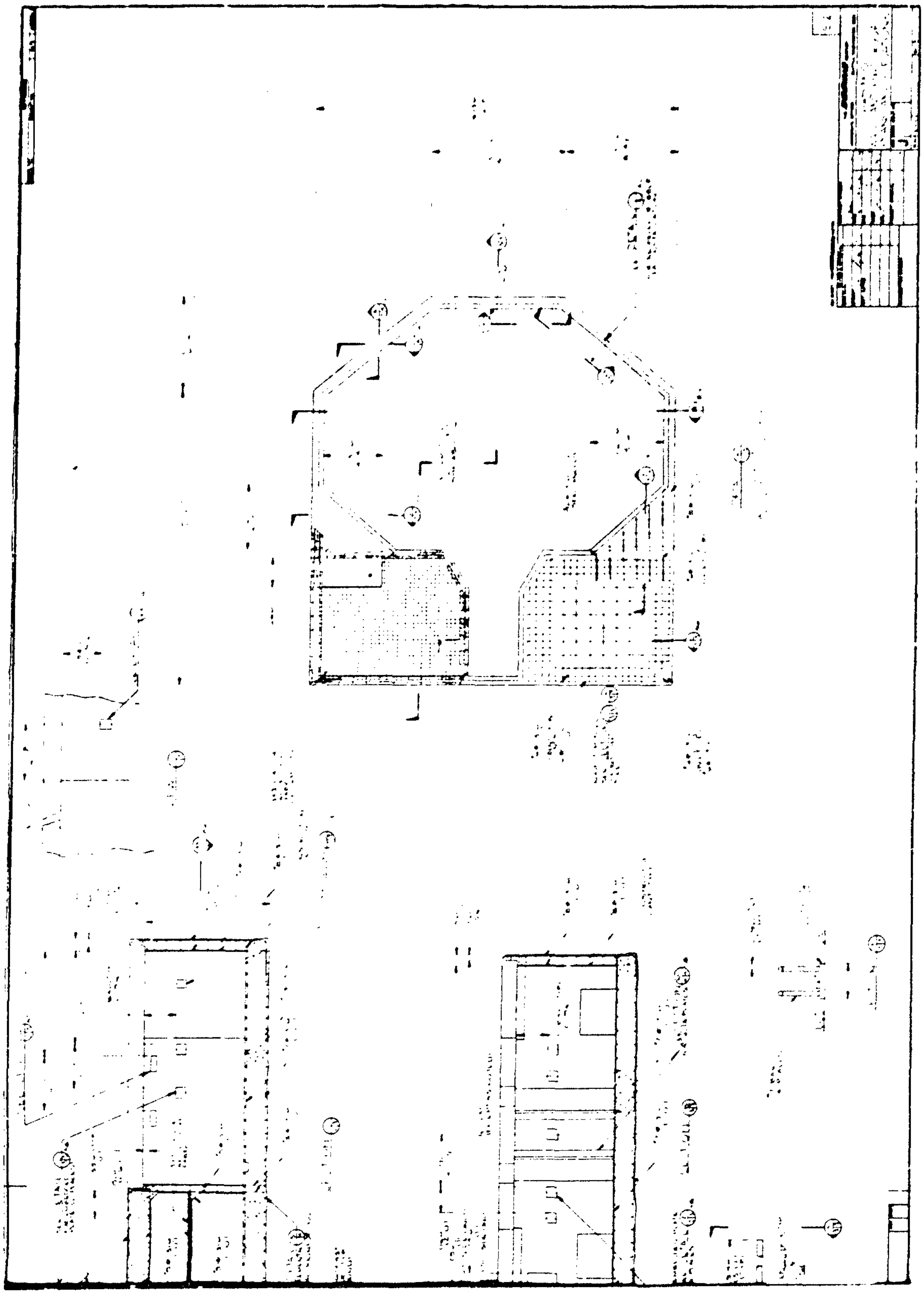
[illegible] ACTUATION SYSTEMS GENERAL SPECIFICATIONS

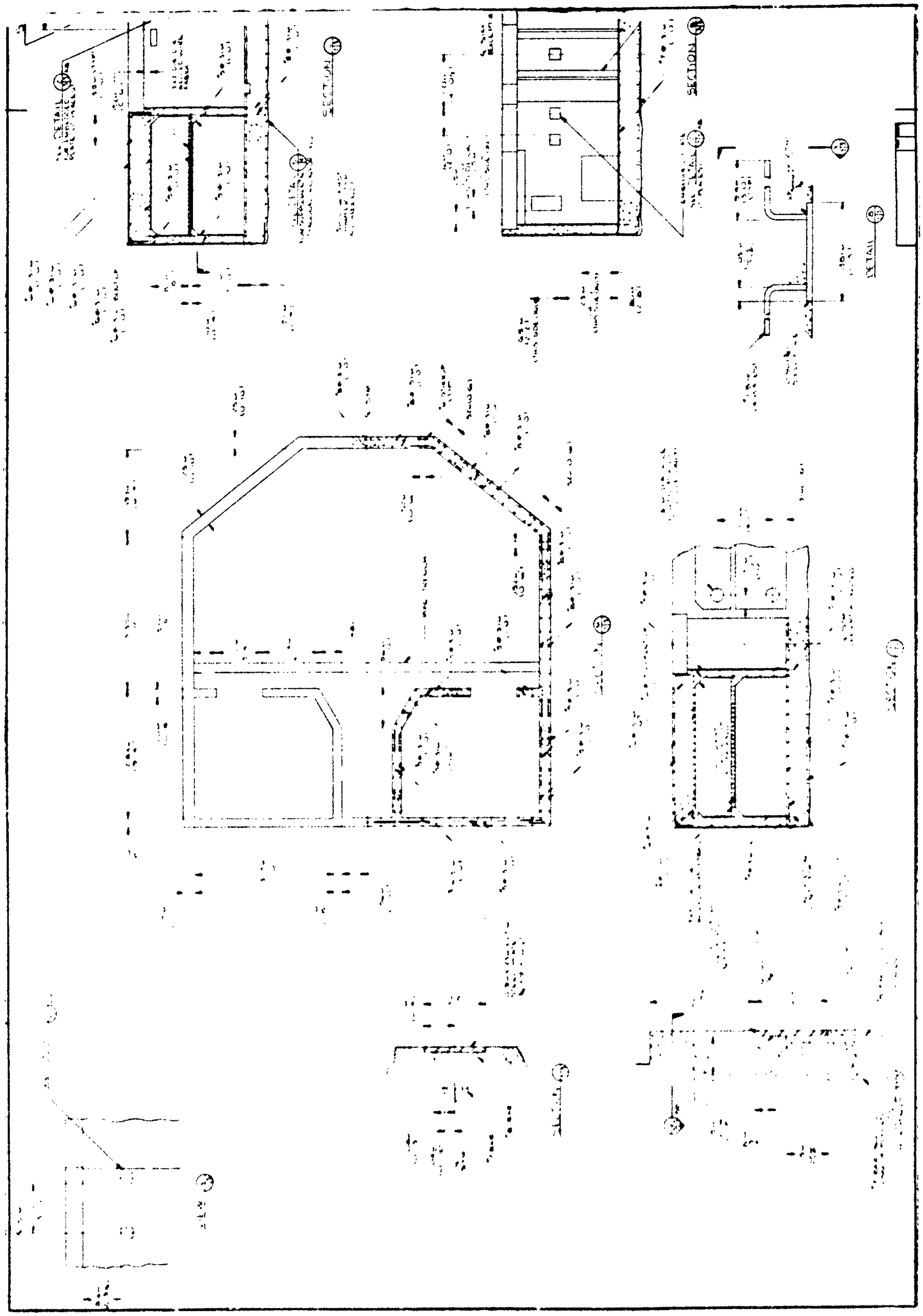
GENERAL NOTES

[illegible]





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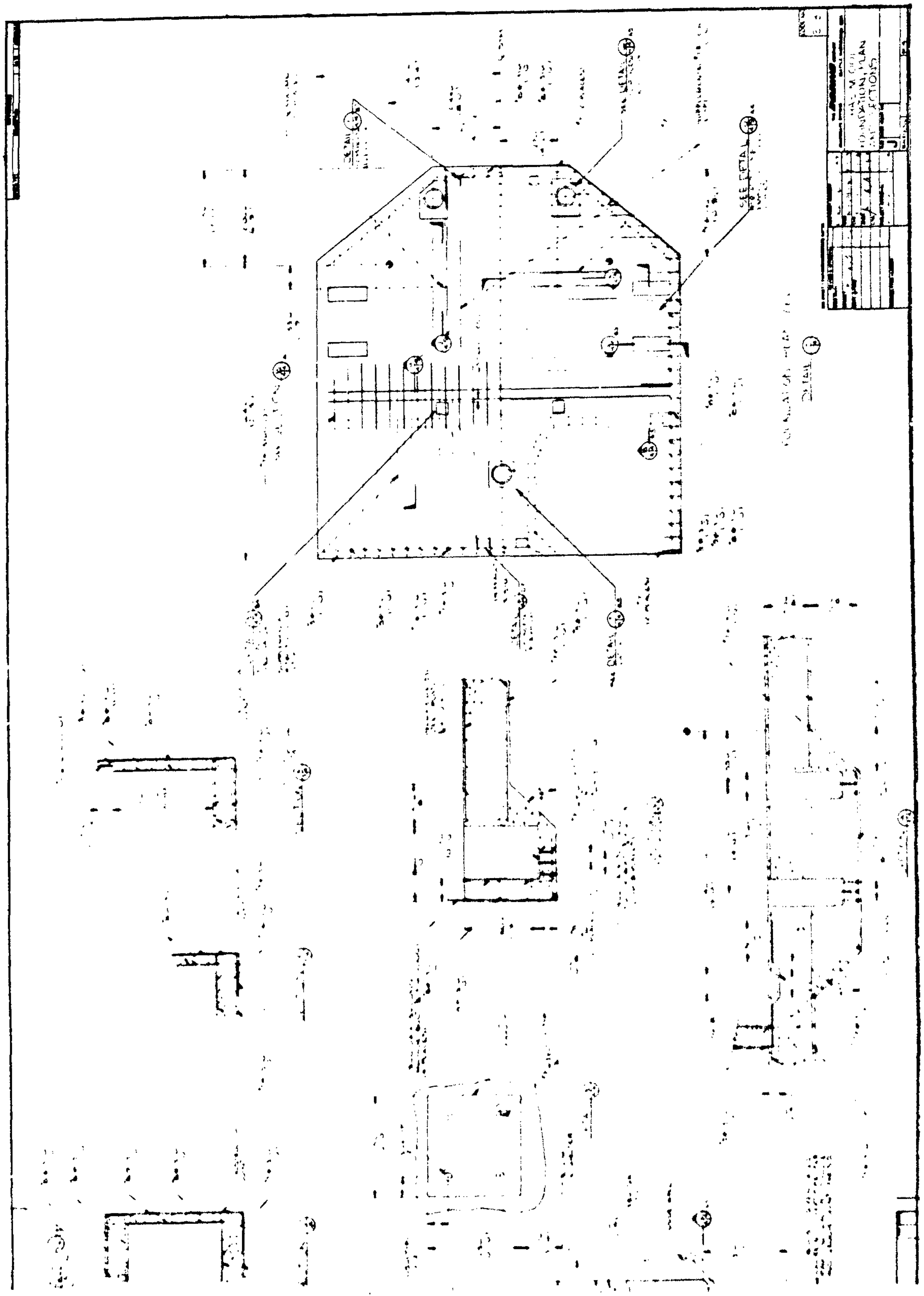

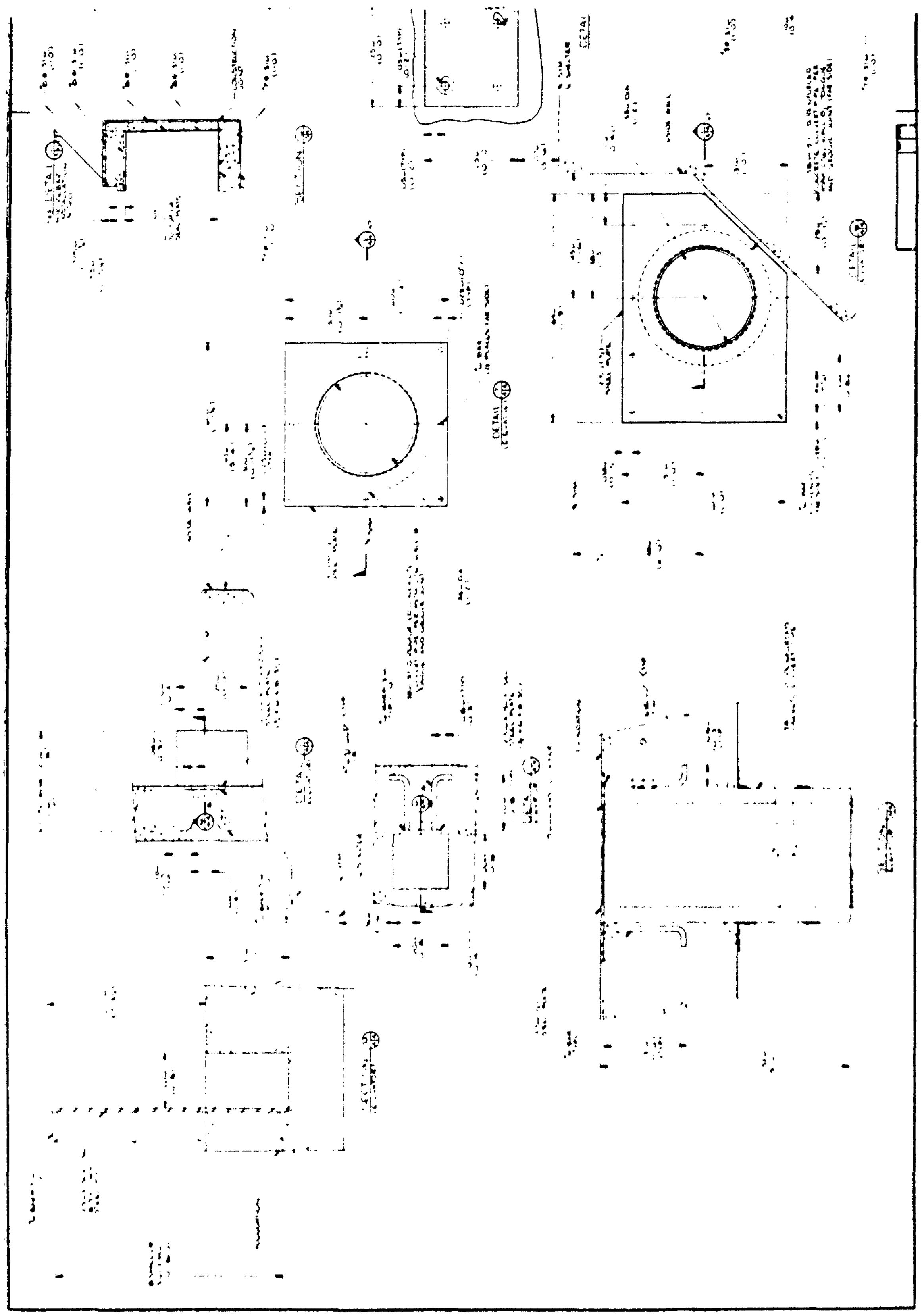

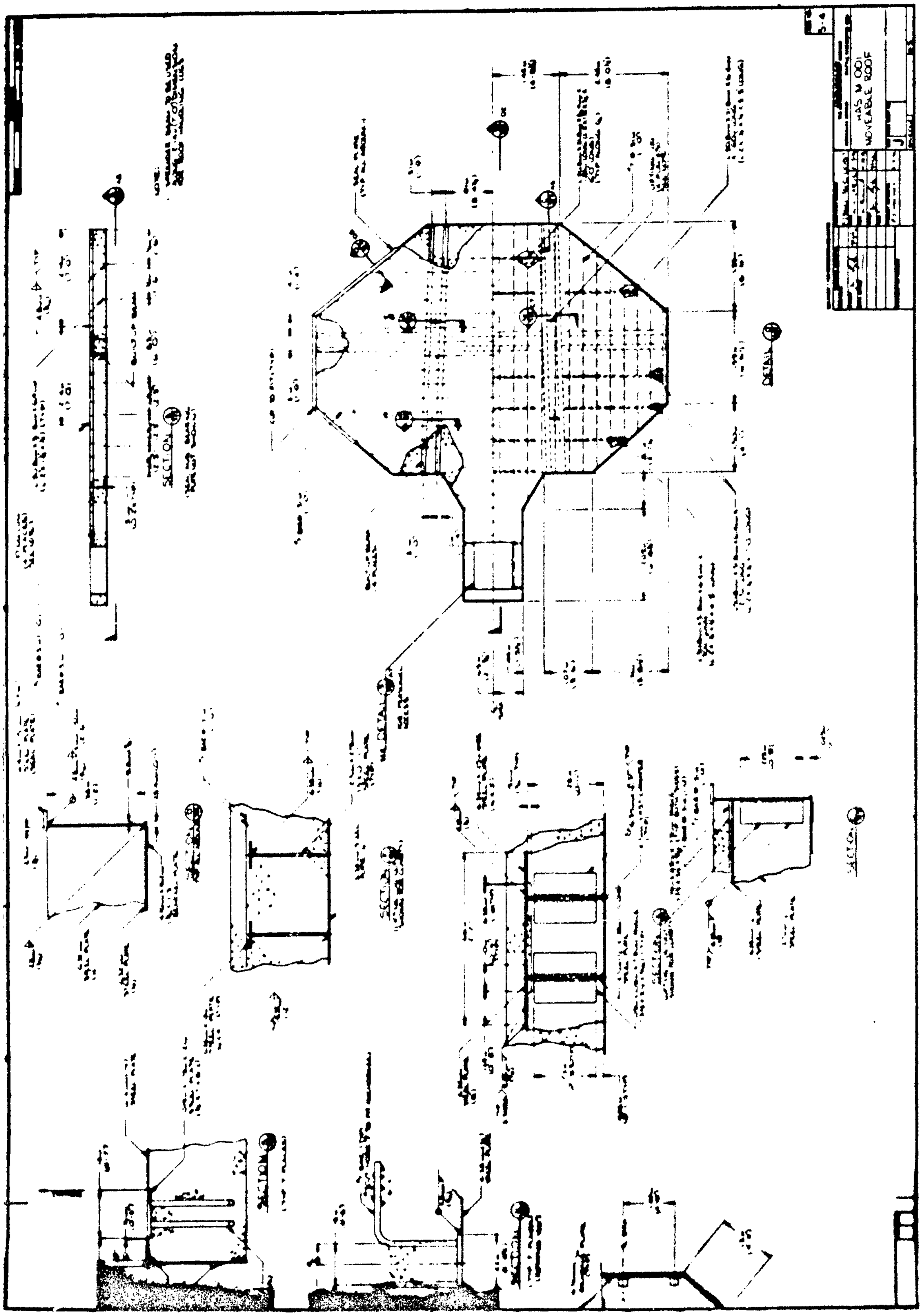
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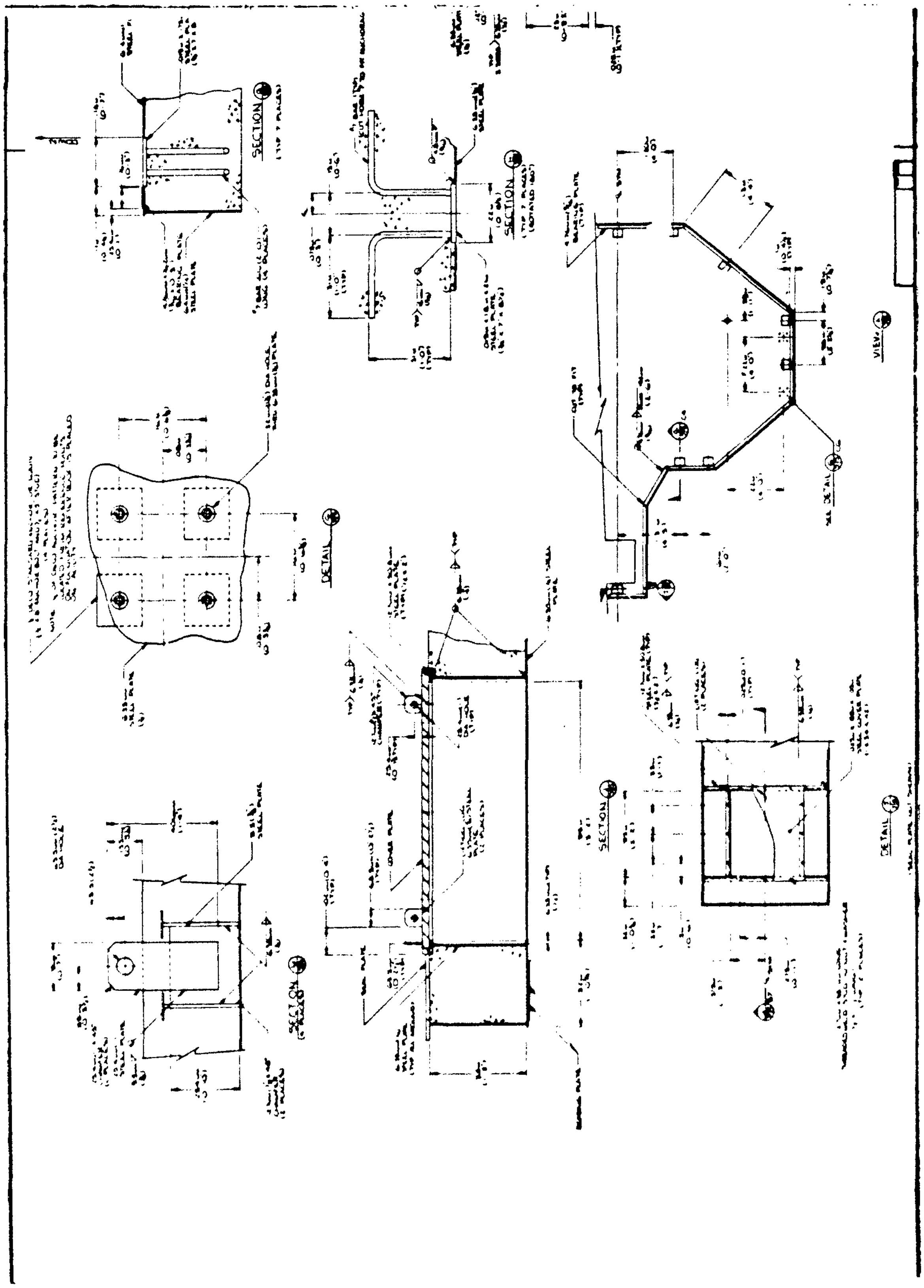
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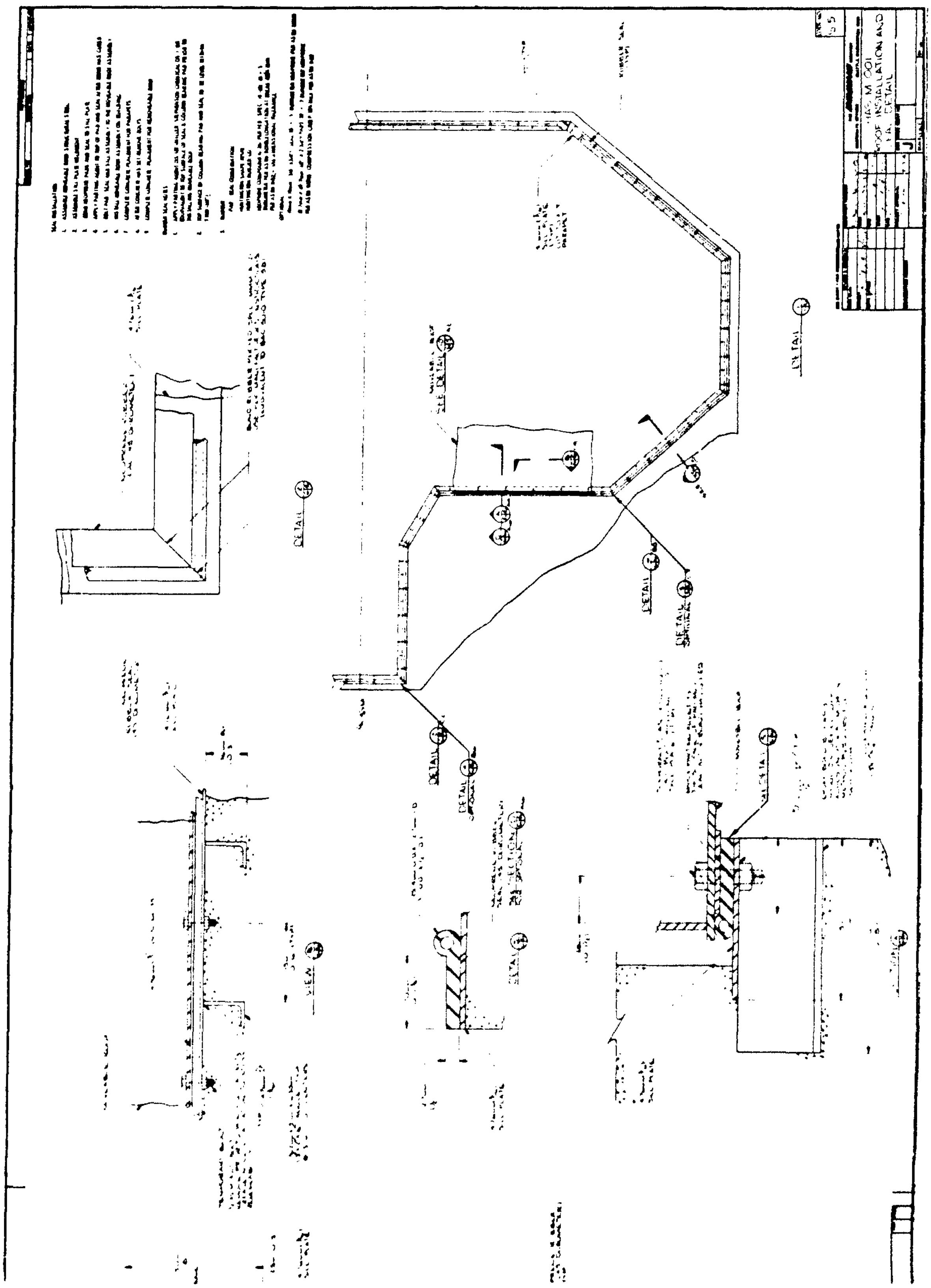
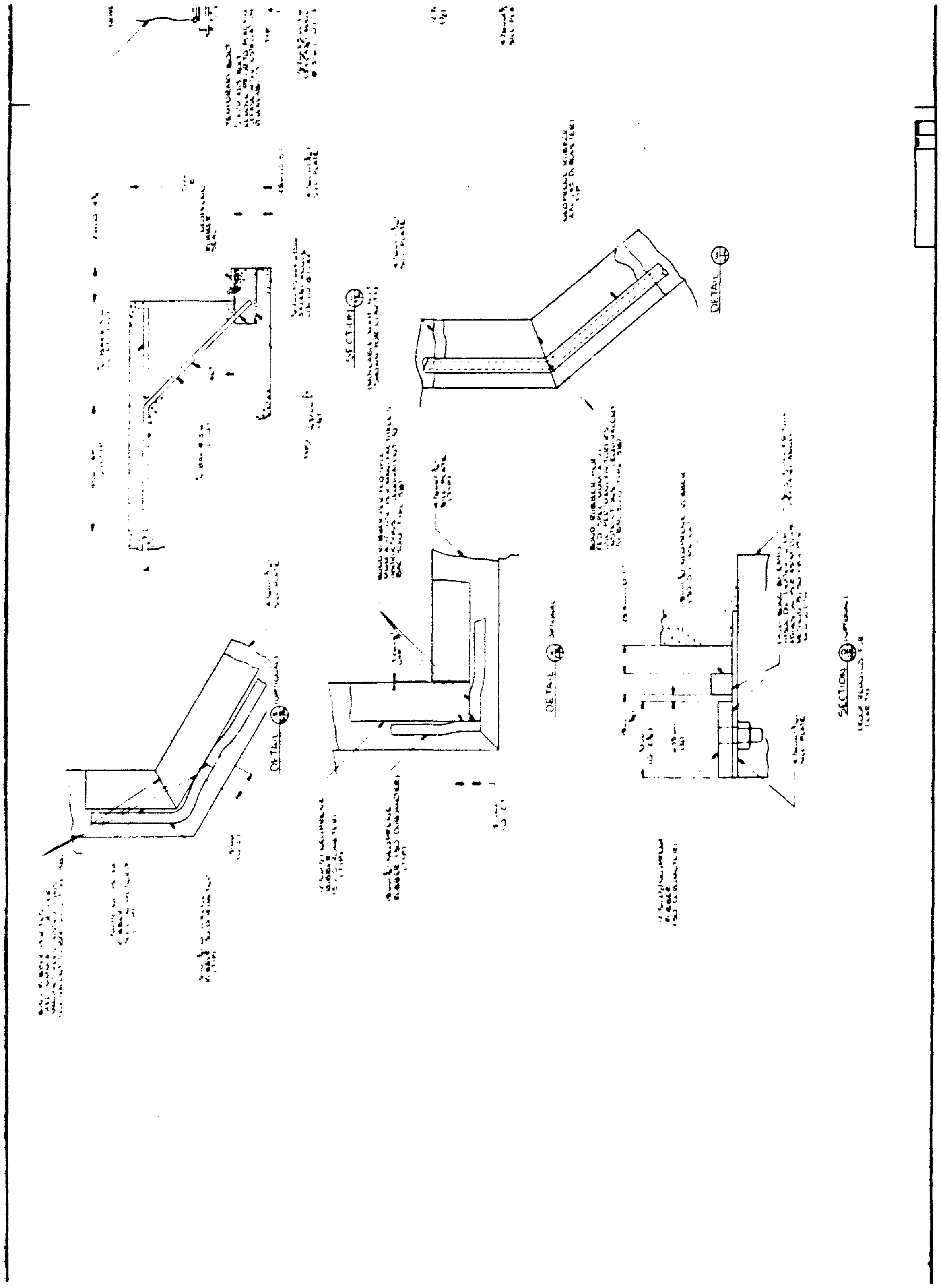
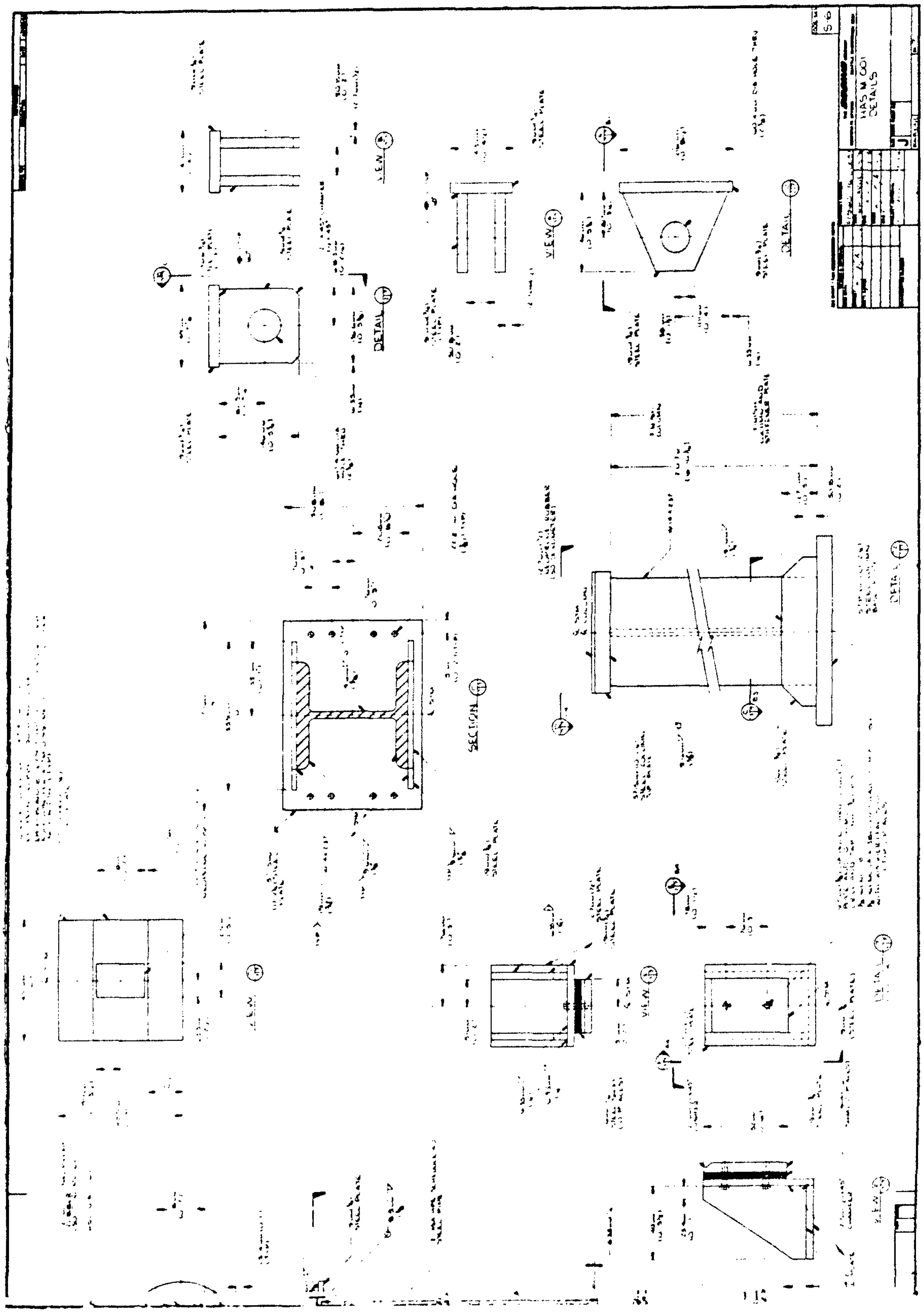
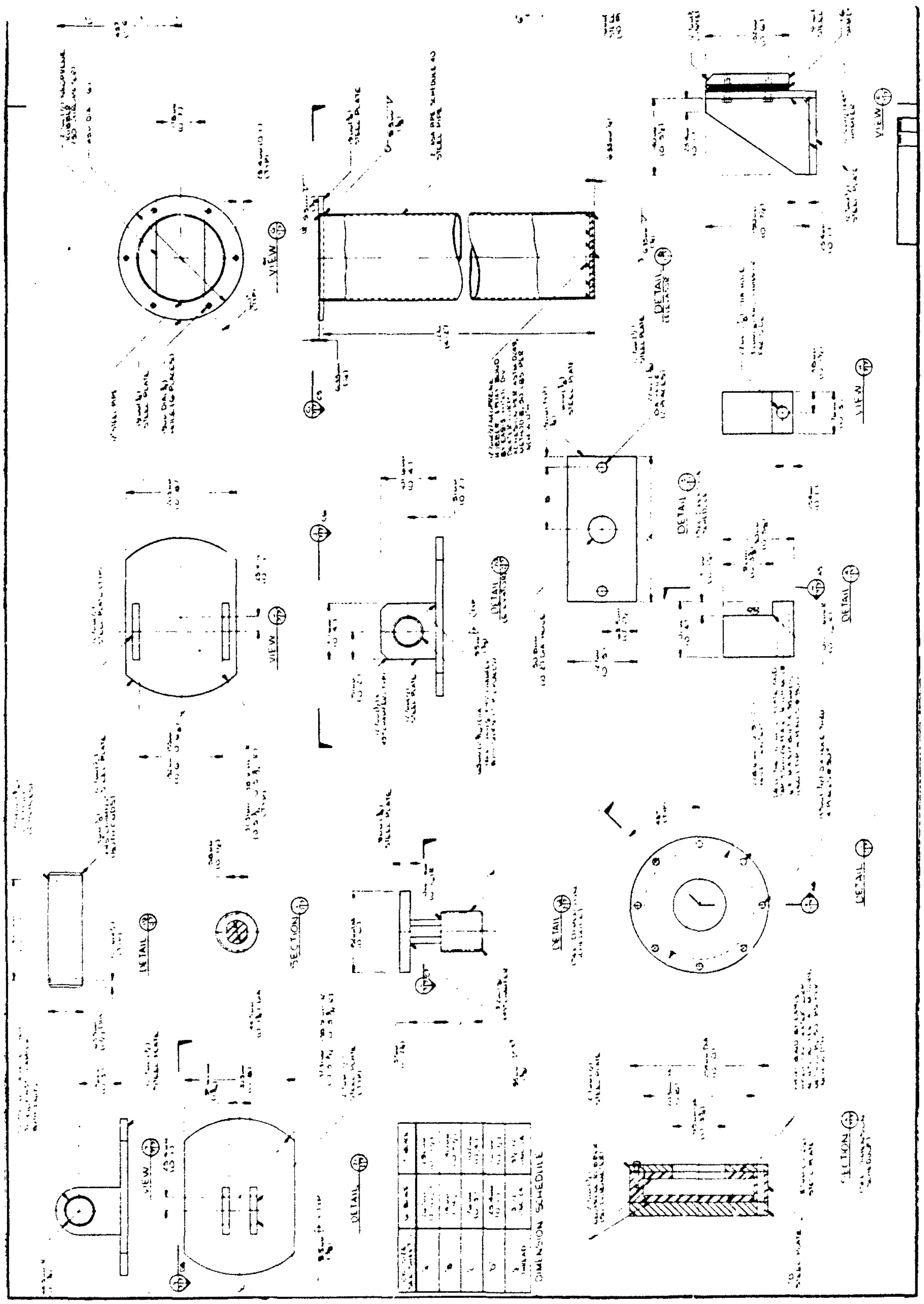
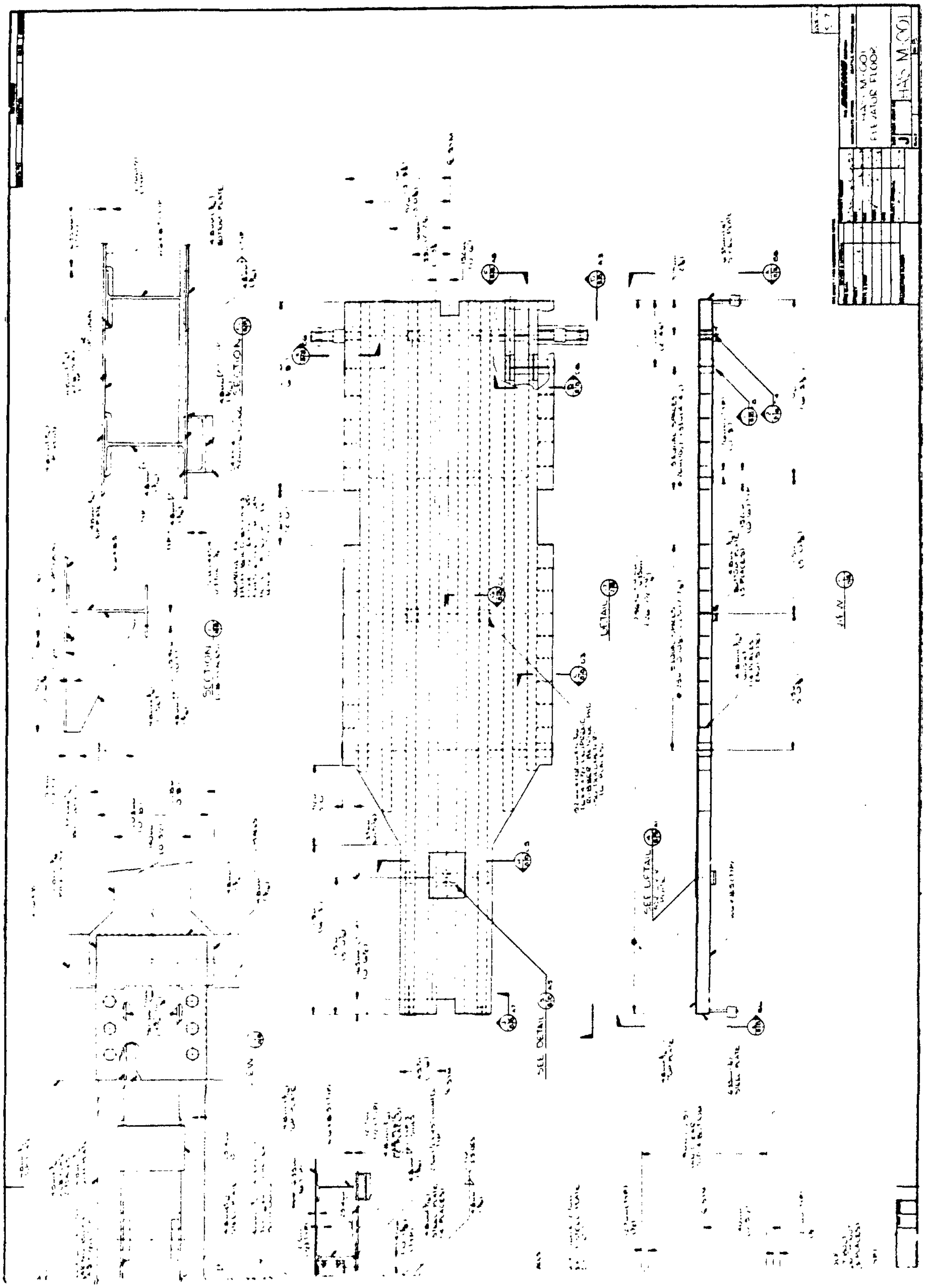
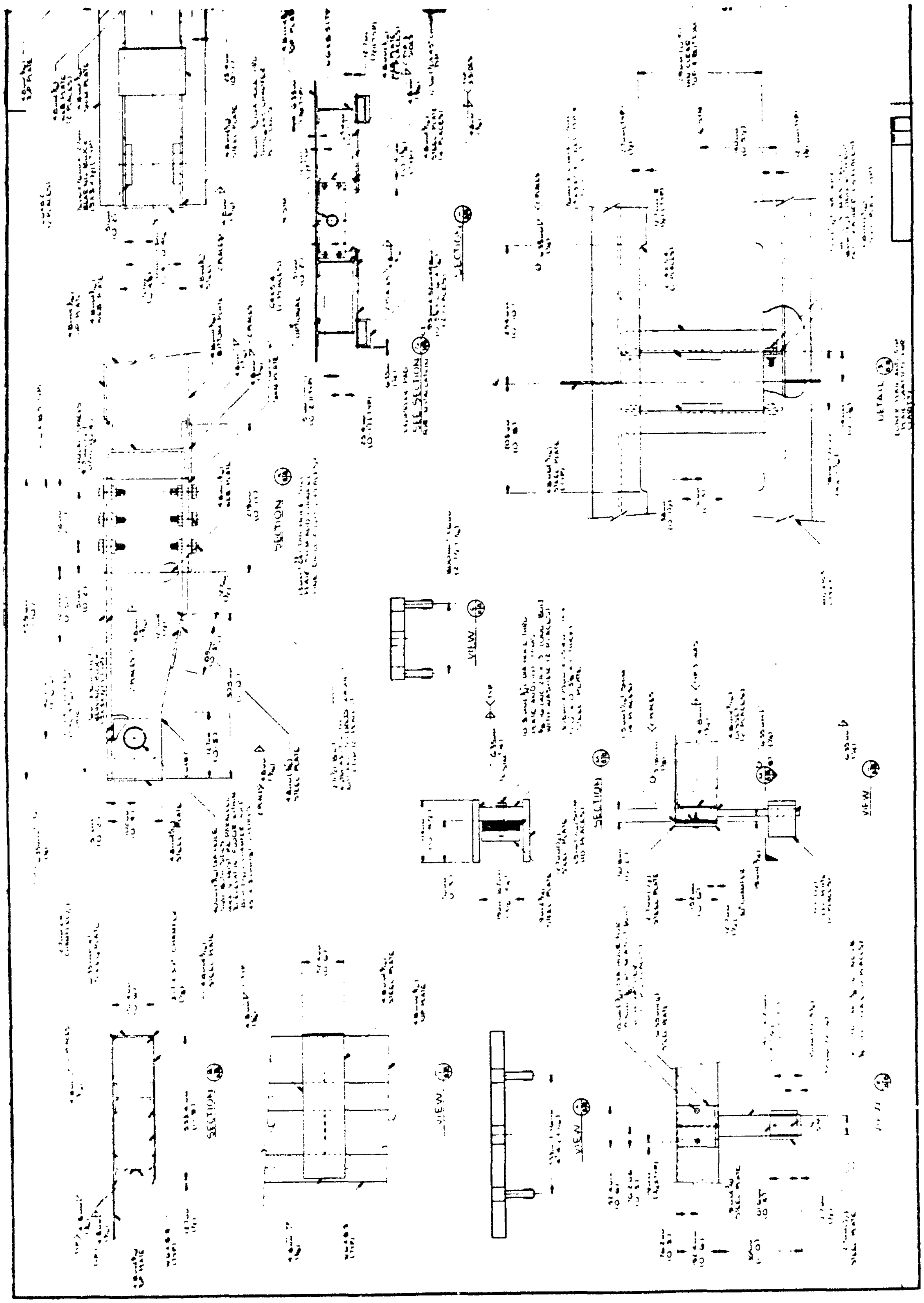


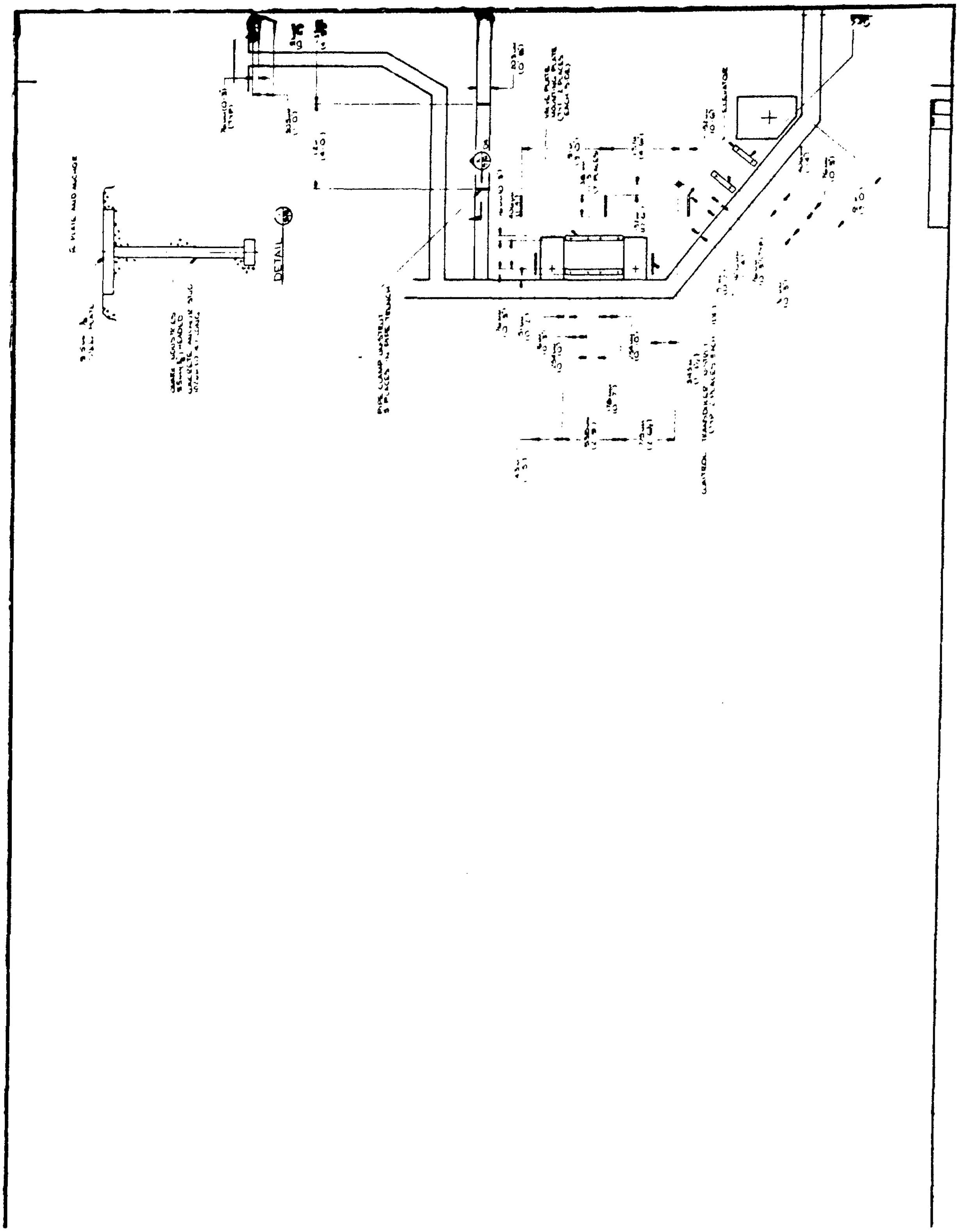


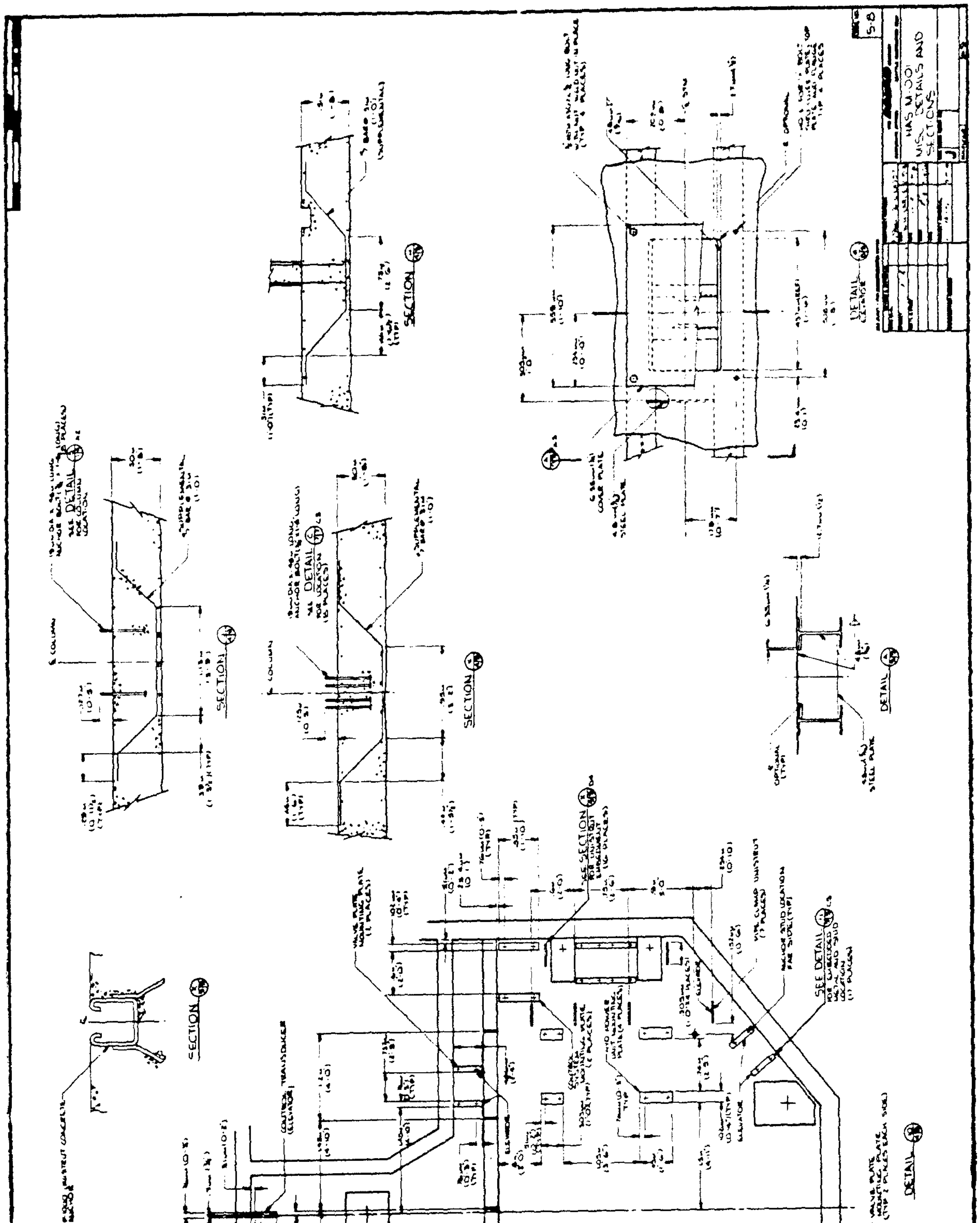


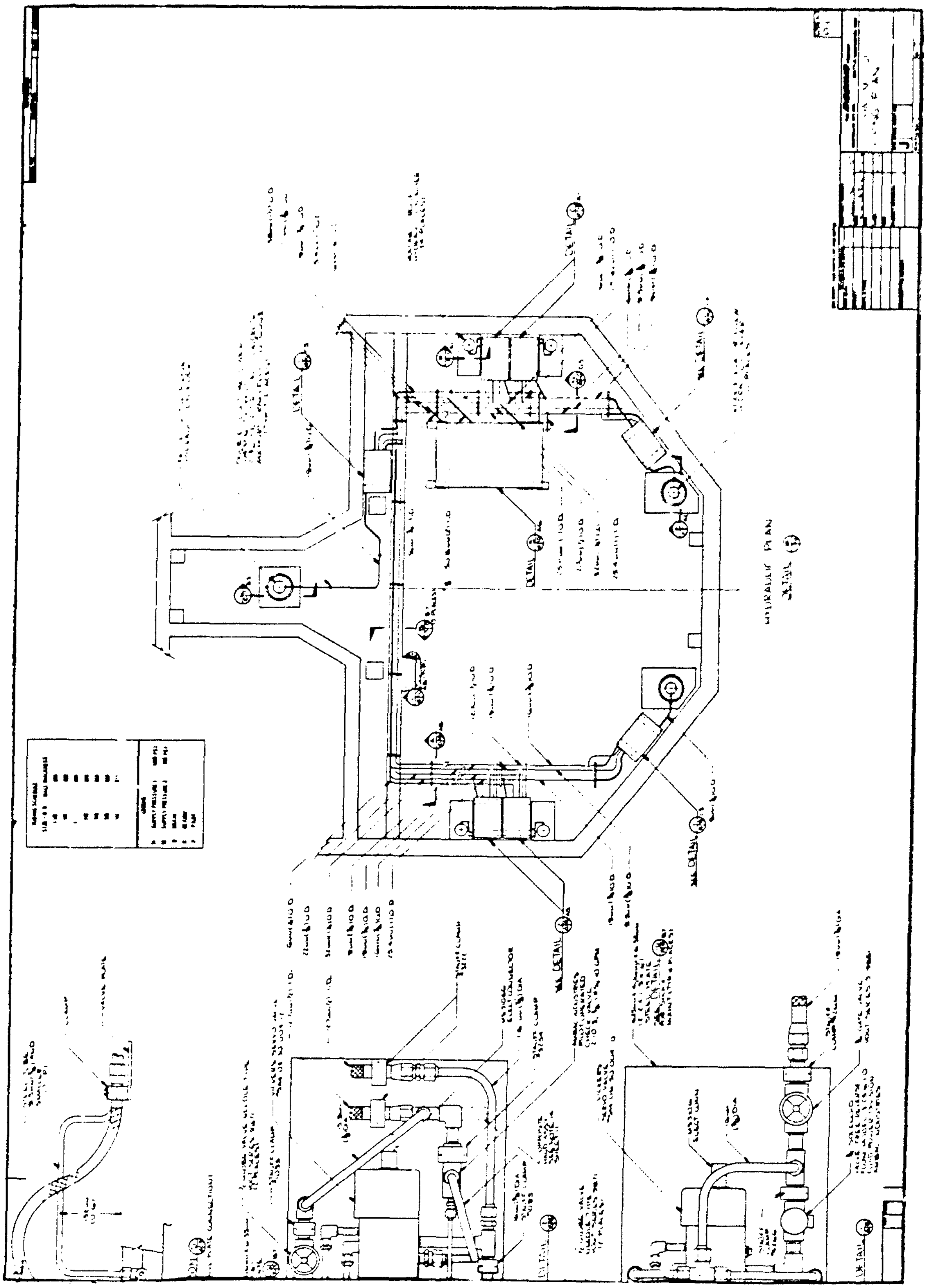


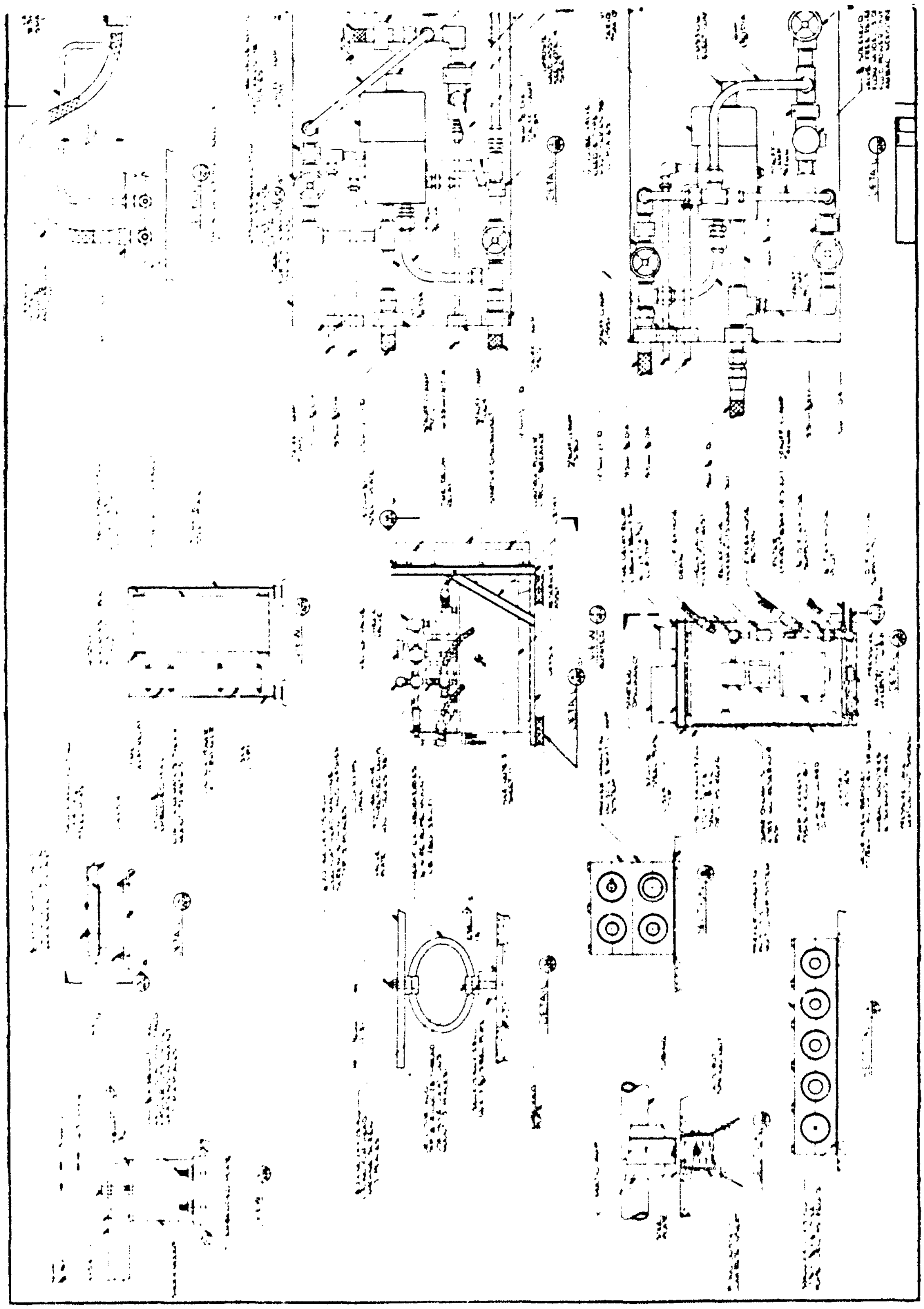


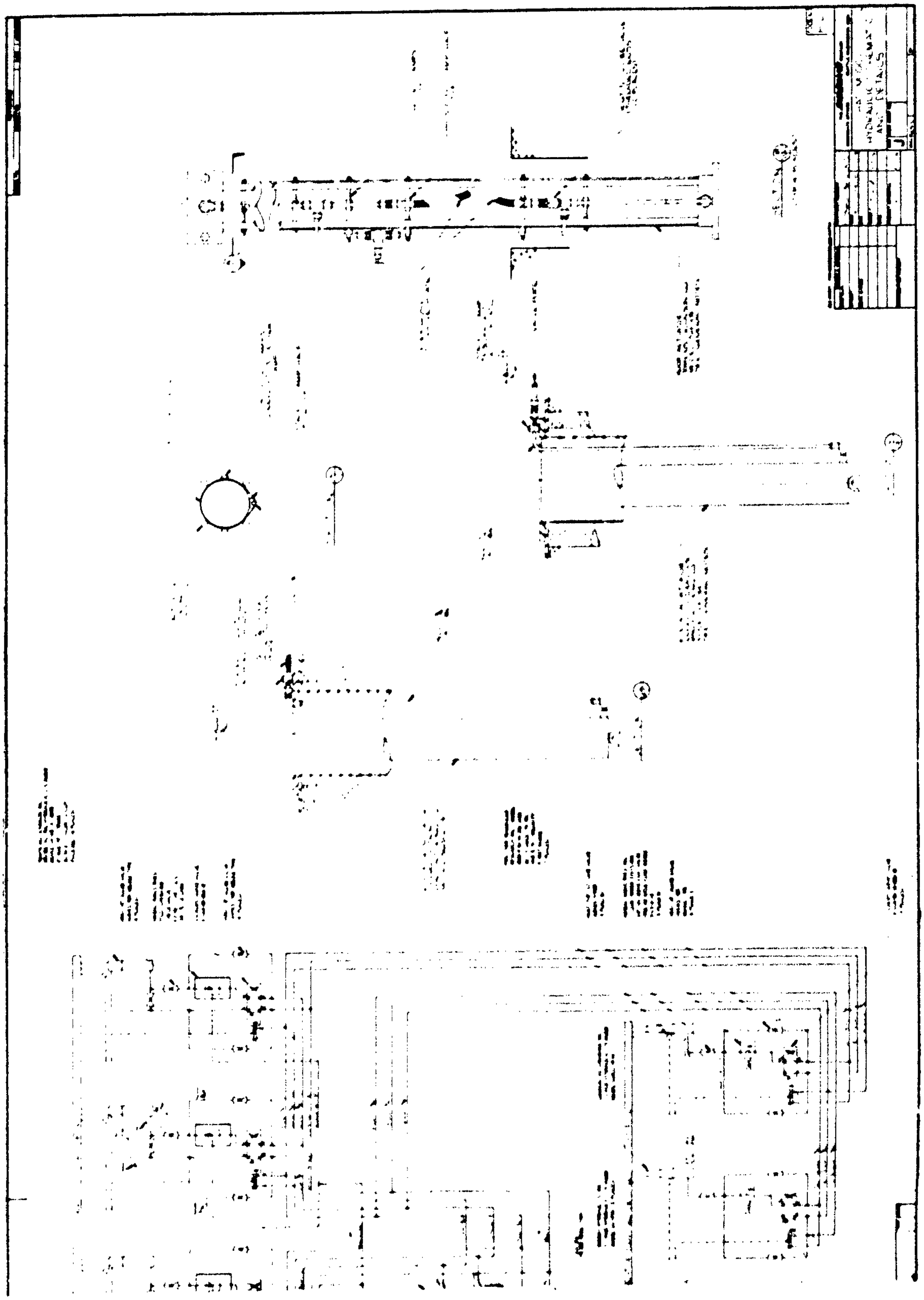


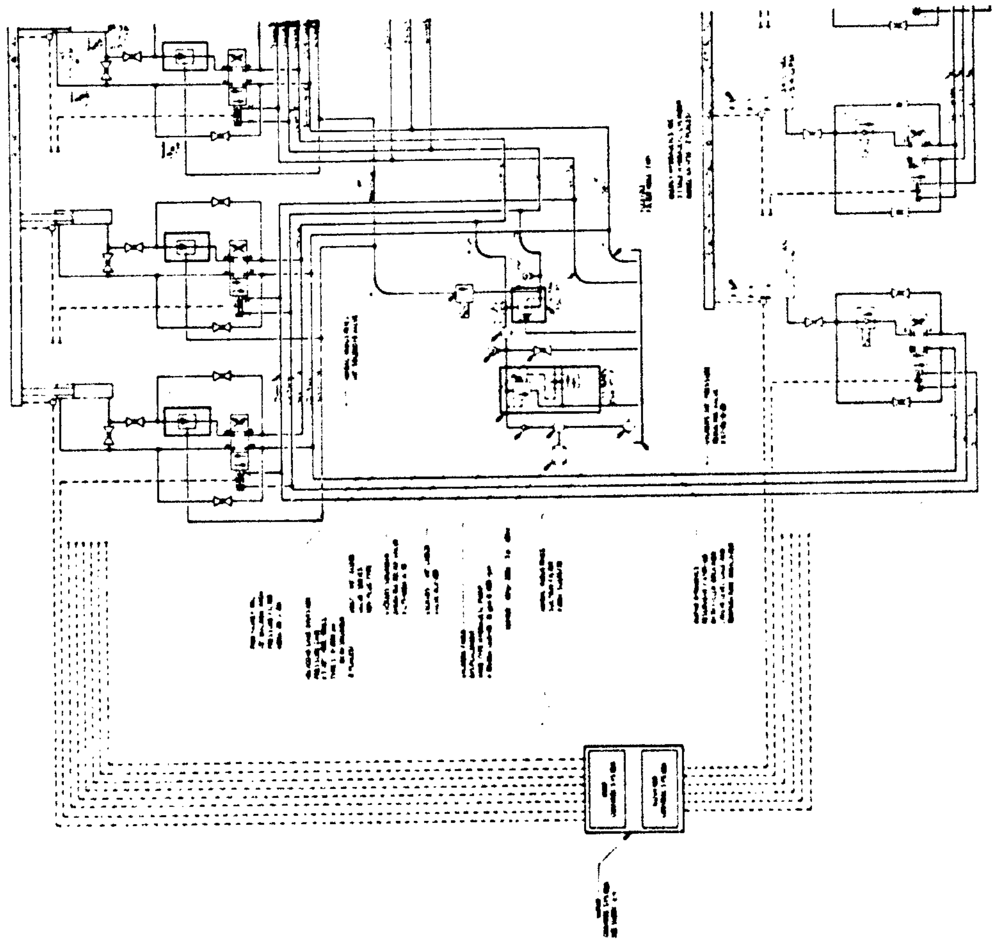

DETAIL
ELEVATOR

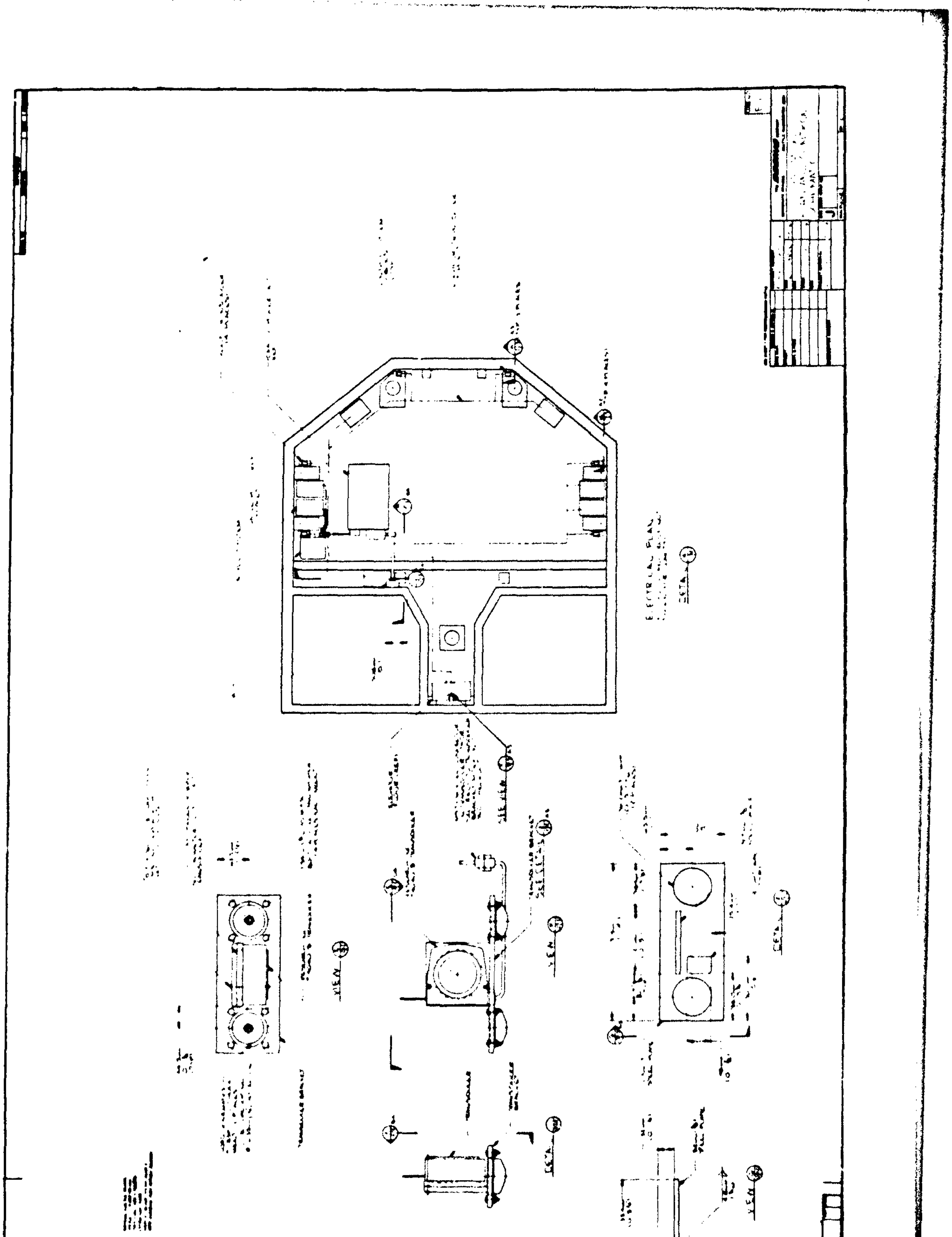


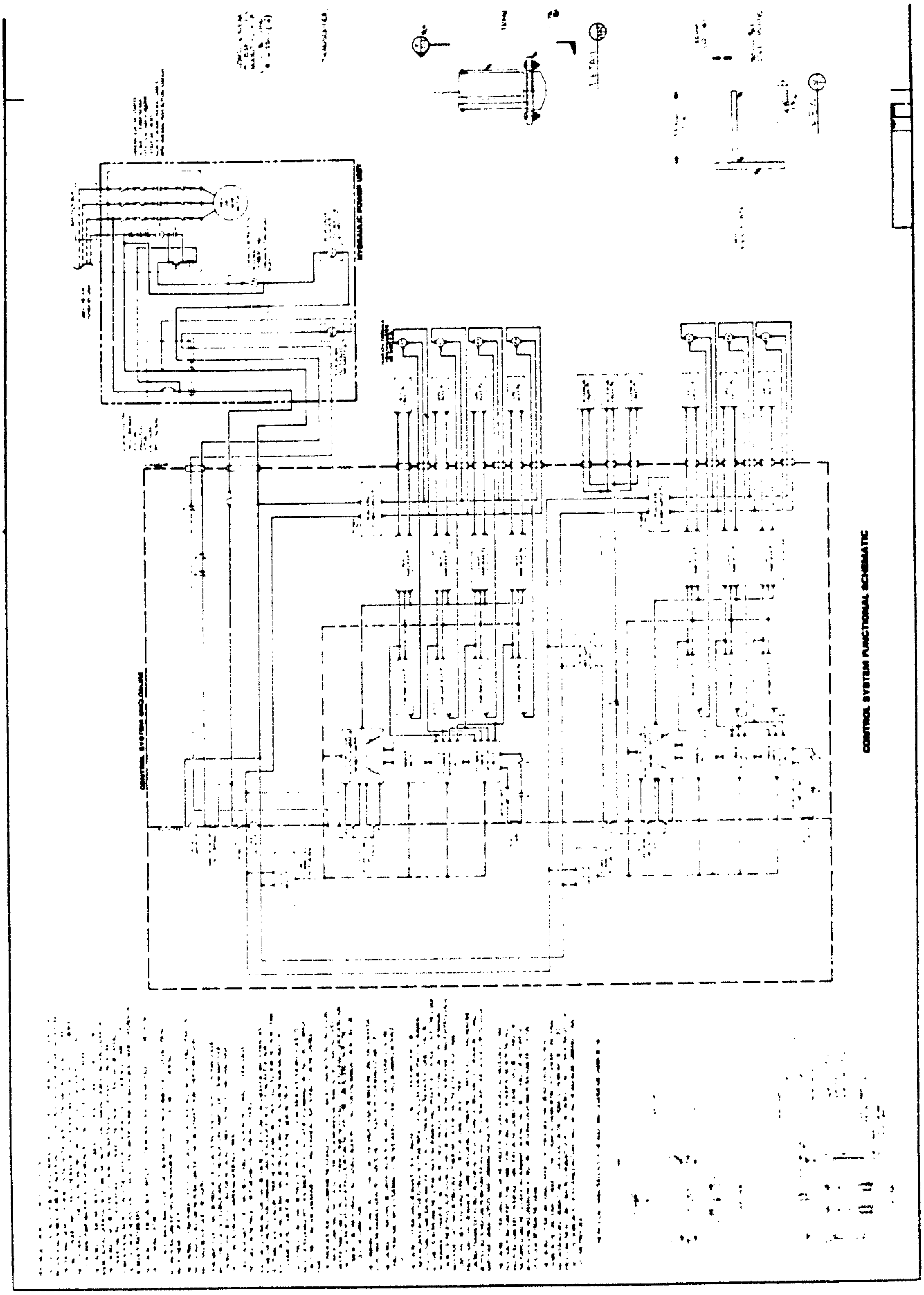




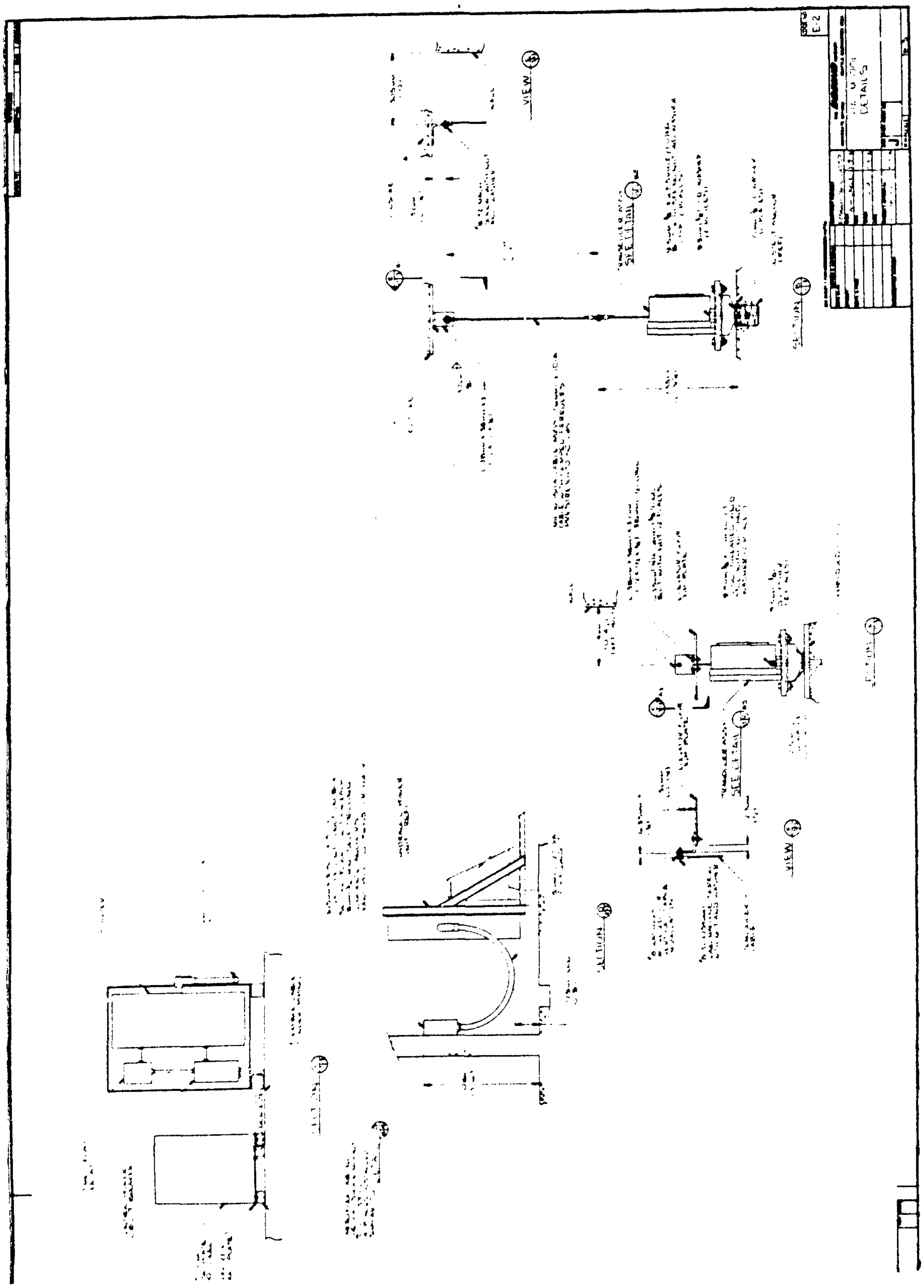


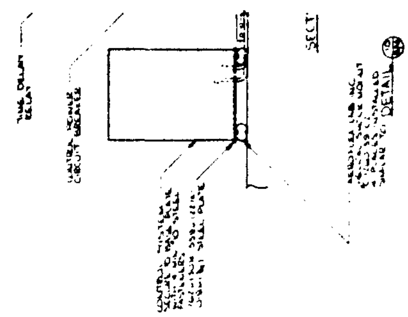






CONTROL SYSTEM FUNCTIONAL SCHEMATIC

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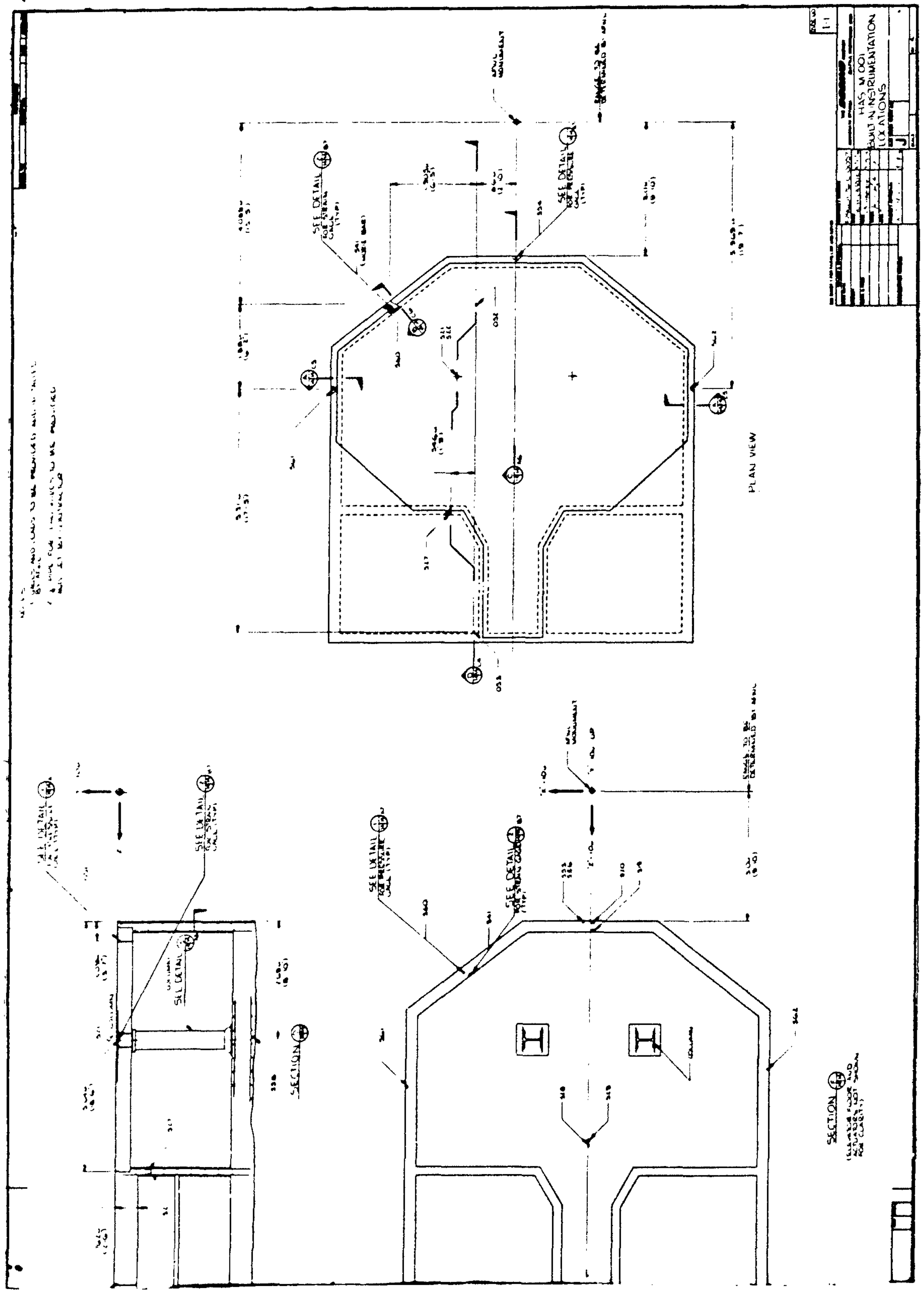

PLAN VIEW
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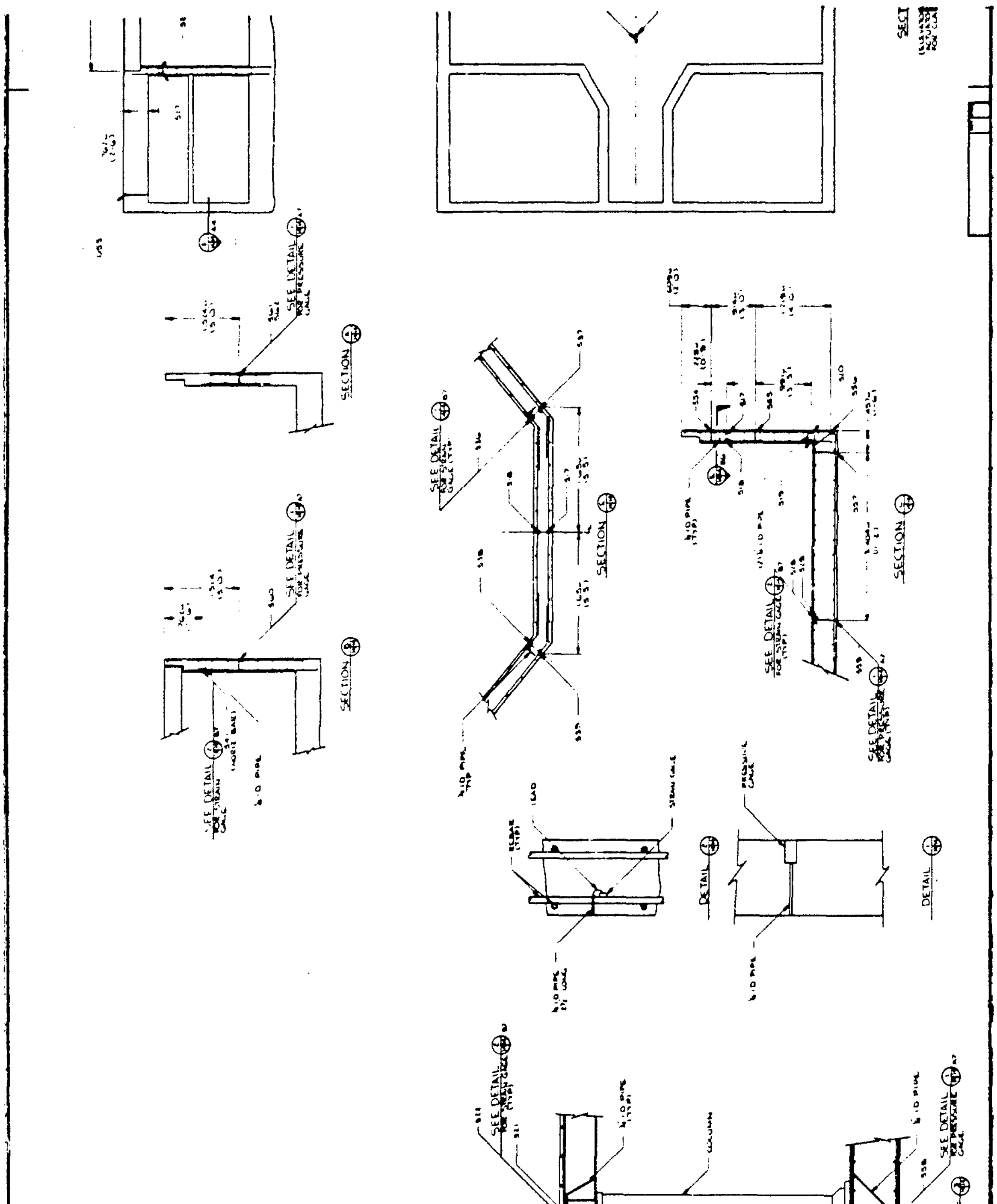
BUILT-IN INSTRUMENTATION LOCATIONS
SECTION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